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Energy Savings and Emission Reduction of Nitrogen Oxides, Particulate Matter, and Polycyclic Aromatic Hydrocarbons by Adding Water-Containing Acetone and Neat Soybean Oil to a Diesel-Fueled Engine Generator

Sheng-Lun Lin,*[†,‡] Wen-Jhy Lee,*[†,‡] Chia-Fon Lee,[§] and Shui-Jen Chen[‖]

[†]*Department of Environmental Engineering, and* [‡]*Sustainable Environment Research Center, National Cheng Kung University, Tainan 70101, Taiwan, Republic of China,* [§]*Department of Mechanical Science and Engineering, University of Illinois at Urbana−Champaign, Urbana, Illinois 61801, and* [‖]*Department of Environmental Science and Engineering, National Pingtung University of Science and Technology, Pingtung 91201, Taiwan, Republic of China*

Dieselhols (blends of diesels, biodiesels, and alcohols) have received considerable attention because of their low emission of CO_2. In this study, new blended fuels were formed by adding 1−3 wt % of water-containing acetone (WA) or dehydrated acetone (AC) into a regular diesel (95−97%) and using 1 wt % of isopropyl alcohol (P) and 1 wt % of neat soybean oil (S) or soybean biodiesel (B) as stabilizers. The blended fuels were tested for their energy efficiencies and pollutant emissions in a diesel-fueled engine generator. Experimental results showed that the fuel blend WA3P1S1, which is composed of 3 wt % WA, 1 wt % P, and 1 wt % neat soybean oil, had a good fuel stability and 1.4−5.5% reduction of brake-specific fuel consumption (BSFC, mL kW^{-1} h^{-1}). The better engine performance of WA3P1S1 was due to its higher fuel oxygen content, more complete combustion, and lower reaction temperature based on the water-cooling effect, which reduced emissions to 6.7−13.6% NO_x, 9.6−33.3% particulate matter (PM), 7.7−14.3 total polycyclic aromatic hydrocarbons (PAHs), and 7.5−11.4% total BaP_{eq}. Nevertheless, using recycled solvents for WA3P1S1, the CO_2 emission was 4.92% lower than a regular diesel. Consequently, WA3P1S1 is a more sustainable fuel that can both save energy and reduce pollution.

1. Introduction

An increased consumption of fossil fuels has raised the crude oil price sharply during the past decade.[1] In addition, the excessive extraction of fuel resources has transformed the underground-based carbons into dispersive gaseous forms, such as carbon dioxide (CO_2), which is one of the major greenhouse gases (GHGs). Thus, developing an alternative fuel with low emissions, high sustainability, and greater cost-effectiveness has become a high priority.

Heavy-duty diesel engines (HDDEs) are widely used in vehicles and generators because of their high fuel efficiency, high power output, and low emissions of traditional pollutants, e.g., carbon monoxide (CO) and unburned hydrocarbon (HC).[2] However, the emissions of particulate matter (PM), sulfur dioxide (SO_2), and polycyclic aromatic hydrocarbons (PAHs) from HDDEs are much higher than those from gasoline engines.[3,4]

Oxygenated additives in diesel fuels, such as ethanol, acetoacid esters, dicarboxylic acid esters, and ethylene glycol monoacetate, have better fuel combustion and lower CO_2 emissions, and many researchers have investigated biodiesel as a more oxygenated alternative to conventional diesel.[5,6] Lin et al.[7] indicated that the addition of 20% by volume of palm biodiesel increased the energy efficiency of diesel by 15.1% and decreased PM_{10} and $PM_{2.5}$ emissions by 3.55 and 7.49%, respectively. Scholl and Sorenson[8] reported that CO, unburned HC, NO_x, and smoke emissions were reduced at 600 kPa brake mean effective pressure (BMEP) when a soybean methyl ester (SME) was used instead of diesel in a compression-ignition (CI) engine.

Fuels with a high cetane number and greater lubricity have also attracted attention. Lin et al.[9,10] indicated that increasing the palm biodiesel and paraffinic palm biodiesel fractions in diesel blends lowered the aromatic contents and further reduced 43.0−90.2% total PAH and 63.1−89.6% total BaP_{eq} emissions. Even so, biodiesel still suffers some disadvantages, such as higher viscosity and lower heating value, which will harm engines and increase fuel consumption.[11] Furthermore,

*To whom correspondence should be addressed: Department of Environmental Engineering, National Cheng Kung University, Tainan 70101, Taiwan, Republic of China. Telephone: 886-6-2757575 ext. 65831. Fax: +886-6-2752790. E-mail: cbmsgml@gmail.com (S.-L.L.); wjlee@mail.ncku.edu.tw (W.-J.L.).

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the higher production cost, associated with the transesterification process, is also a major barrier to wide acceptance. Therefore, the addition of neat soybean oil in diesel is examined in this study.

Bioethanol is another bio-oxygenated additive that could potentially improve combustion and reduce the emissions of CO, HC, and PM.[12] However, ethanol is not suitable for CI diesel engines without engine modification, because it has a low cetane index and low vapor pressure. Additionally, the ethanol used as a diesel additive requires a purity of 99.5%, while the simple distillation process can only concentrate it to 95.6%.[13,14] Joel et al. estimated that the ethanol dehydration process would cost 14% in net energy balance over the whole bioethanol production process.[15] These factors present significant obstacles to the use of 99.5% ethanol as a fuel additive.

Dieselhol (blends of diesels, biodiesels, and alcohols) have been investigated as a new oxygenated fuel because a lower viscosity of alcohol can balance the high viscosity of biodiesel or neat soybean oil. Furthermore, the above disadvantage of alcohol can be abated by being blended with either the biodiesel or neat soybean oil, which both have a high cetane index and heating value. Shi et al.[16] showed that a blend of 80 or 85% diesel with 20 or 15% BE (methanol soyate contains 20 vol % ethanol) has significantly lower PM and CO emissions but a higher NO_x emission. Kwanchareon et al.[17] proposed similar results using a blend of 80% diesel, 15% biodiesel, and 5% ethanol. The emissions of CO and HC were found to be obviously reduced at high engine load, whereas the NO_x emission was increased. However, the high production cost of pure alcohol and biodiesel hinder the practical use of dieselhol in HDDEs. Specifically, the use of pure ethanol costs extra energy in dehydration processes, while using biodiesel spent extra energy and produced a huge amount of unfavorable byproduct, glycerol, in the transesterification reaction. Therefore, this study tried to use the solvent, which were recycled or produced by a simpler process as the feedstock of blended diesels.

Acetone and isopropyl alcohol are both recognized as two major industrial waste solvents, which are also oxygenate and co-solvent, respectively, to fuel blends. Hong et al.[18] reported that acetone-blended normal heptane could effectively reduce soot formation in a high-pressure shock tube (HPST) test. Zhou and Rhue revealed that isopropyl alcohol could be used as a co-solvent to stabilize water and oil mixing phases.[19] To extract usable energies and reduce the emissions of CO_2 and regular pollutants, the blends of water-containing/pure acetone, soybean crude oil/biodiesel, and a regular diesel are investigated in the current study.

Acetone with added water was used to simulate the waste solvent without dehydration, while pure isopropyl alcohol

was used as a co-solvent to stabilize the water content in diesel fuels. Additionally, neat soybean oil was used instead of biodiesel to reduce the cost and secondary waste of the transesterification process. In addition, pure acetone (AC) and soybean biodiesel (B) were still added to form diesel blends for comparisons. The experimental work included the fuel blending, stability test, and the examination of energy efficiencies and pollutant emissions of fuel blends in a heavy-duty diesel-fueled engine generator (DFEGs).

2. Experimental Section

This research starts from the material preparation to the fuel blending processes, stability, and DFEG tests, as shown in Figure 1.

2.1. Fuel Blending. The premium diesel fuel (PDF) produced by the Chinese Petroleum Corporation (CPC) was used as the base fuel. Analytical-grade acetone and isopropyl alcohol (P), which were used to simulate the recycling or fermentation-produced solvents, were obtained from Mallinckrodt Chemicals (99.5% purity). The commercial neat soybean oil was supplied by the Taiwan Sugar Corporation. The soybean biodiesel used in this study was produced from the methanol and aforementioned neat soybean oil by a homogeneous NaOH-catalyzed transesterification process. The reaction time (min), methanol/oil ratio, and catalyst loading (g of NaOH/L), which would sensitively affect the biodiesel production yield, were optimized by the response surface method. The biodiesel yields (biodiesel/oil, wt %) were measured as the responses with vary times (10−50 min), methanol/oil ratios (3−9), and catalyst loadings (3−10 g of NaOH L^{-1}). The specific levels of NaOH and methanol/oil mixture were first added to a 4 L container and reacted for 10−50 min in different tests with a magnetic stirrer at 1000 rpm. The mixtures were set in a separating funnel and left for 6 h for the glycerine to settle at the bottom by gravity. The separation processes were carried out by "washing" steps (4 times with tap water). Furthermore, the upper layer biodiesel were then collected and heated to drive away the trace solvent and water. After a series of tests, the optimized reaction time, methanol/oil ratio, and catalyst loading were 30−35 min, 6, and 5−7 g of NaOH L^{-1}, respectively. Full-scale transesterification was carried out after establishing the optimized condition and approaching a high production yield in the range of 95−98%.

All blending processes in this study were achieved using a lab-scale 1 L mixer at 3000 rpm for 15 min. Water-containing acetone (WA) was first prepared by blending 5 wt % water with 95 wt % acetone to simulate the product of an industrial simple distillation recycling process. Furthermore, WA was blended by 1, 5, 10, and 20% in mass with diesel as a preliminary test to find the maximum stable additive ratio. The result showed that separation layers were formed in WA5, WA10, and WA20 (the number represents the mass percentages of WA in each blend), and therefore, these blended diesels were not stable enough to be used in a DFEG. Thus, 1 wt % pure isopropyl alcohol (P) and 1 wt % neat soybean oil (S) were further added as stabilizers in diesel blends. In addition, pure acetone (AC) and soybean biodiesel (B) were used to replace WA and S in acetone−(isopropyl alcohol)−soybean oil (APS) blends to examine the effects of the different heating values and water contents of additives. The fuel blends tested in this study are listed in Table 1.

2.2. Fuel Stability Test. The blended diesels were examined by both the gravitational and centrifugal stability tests. In the gravitational test, the appearance of a blend fuel was recorded over a 30 day period to examine its stability during 1 month of storage. Furthermore, a centrifugal stability test at 5000 rpm for 15 min was conducted to simulate the long-term stability of blending diesel fuel. After gravitational and centrifugal stability tests, the different degrees of phase separations in the blended fuels formed an empirical index of stabilities. Figure 2 shows the four levels of fuel stability, including (a) one-phase clear liquid,

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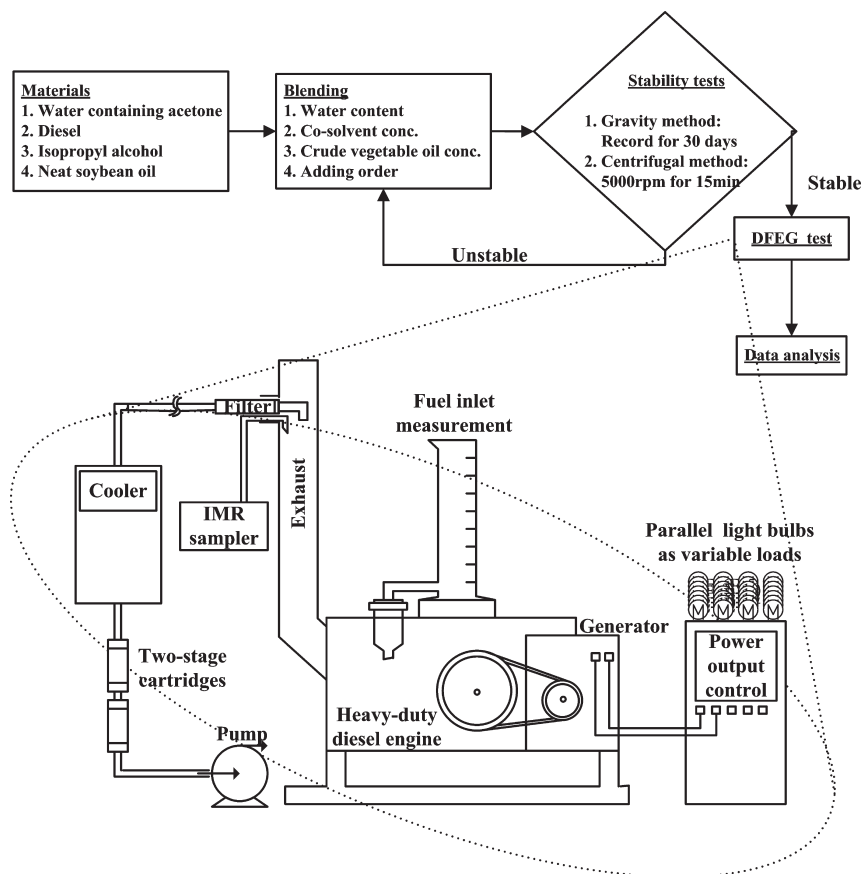
Figure 1. Research scheme and DFEG sampling system.

Table 1. Diesel Blend Phase Stabilities (after Centrifugation) and Calorific Values[a]

blends	D (wt %)	S (wt %)	B (wt %)	WA (wt %)	AC (wt %)	P (wt %)	stability	CV (MJ kg^{-1})
regular diesel	100						one phase	41.66
S1	99	1					one phase	41.64
B1	99		1				one phase	41.62
WA1P1S1	97	1		1		1	one phase	41.38
WA2P1S1	96	1		2		1	one phase	41.24
WA3P1S1	95	1		3		1	one phase	41.09
WA4P1S1	94	1		4		1	two phases	
WA5P1S1	93	1		5		1	two phases	
WA1P1B1	97		1	1		1	one phase	41.37
WA2P1B1	96		1	2		1	one phase	41.22
WA3P1B1	95		1	3		1	one phase	41.08
AC1P1S1	97	1			1	1	one phase	41.40
AC2P1S1	96	1			2	1	one phase	41.27
AC3P1S1	95	1			3	1	one phase	41.13
AC1P1B1	97		1		1	1	one phase	41.37
AC2P1B1	96		1		2	1	one phase	41.22
AC3P1B1	95		1		3	1	one phase	41.08

[a] D, regular diesel; S, neat soybean oil; B, soybean biodiesel; WA, water-containing acetone; AC, pure acetone; P, isopropyl alcohol; CV, calorific value.

(b) one-phase liquid crystalline, (c) two-phase liquid crystalline, and (d) two-phase clear liquid. The order of stability is as follows: a > b > c > d. In two-phase clear liquid, a greater ratio of the separated layer means less stability. The blended diesel fuel with a "one-phase clear liquid" condition is a stable diesel fuel and can be further used in the diesel engine test.

2.3. Diesel Engine Generator Test. The fuel consumption rates, combustion efficiencies, and pollutant emissions were examined in a DFEG. A four-stroke, single horizontal cylinder engine made by Yanmar S.P. Co., Ltd., Thailand, was employed in this study (Table 2). During the diesel engine test, the generator loads were controlled by various resistances with 100 parallel bulbs, equivalent to 5 kW (Figure 2). Three generator loads were studied as 0 (idling), 1.6, and 3.2 kW by tuning the engine rotational speed to simulate the idling operation and at 40 and 80% of the maximum load, respectively. The 80% load was set for a normal standby-rated engine test that have 20% less from the maximum for a safety factor, while the 40% load represents the mid-low of engine operation. These three loads could further perform complete engine functional and emission curves by operating the engine with a steady test, which provided a lower cost. Additionally, the fuel consumption was measured by a 1 L graduated cylinder inlet unit (Figure 2). Generally, the brake-specific fuel consumption (BSFC) of a generator is expressed as the fuel consumption volume per unit of electrical energy generated (mL kW^{-1} h^{-1}).
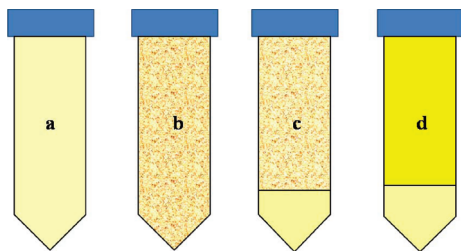
Figure 2. Four stability levels: (a) one-phase clear liquid, (b) one-phase liquid crystalline, (c) two-phase liquid crystalline, and (d) two-phase clear liquid.

Table 2. Specifications of the DFEG

item	
manufacturer	Yanmar S.P. Co., Ltd., Thailand
type	four-stroke, single horizontal cylinder engine
ignition	compression ignition
injection system	direct injection
starting system	hand crank
cooling system	water cooled
lubrication system	forced-feed type
exhaust system	muffler
air-cleaning system	oil-bath type
fuel	diesel
displacement volume (cm^3)	583
bore × stroke (mm)	88 × 96
rated engine speed (rpm)	2400
rated output power (kW)	4.0
torque (kg m)	1.63
fuel consumption (L/h)	2.93

The pollutant monitoring system was installed as Figure 1. The gaseous pollutant emissions in the tail pipe exhaust were monitored by an online device, IMR2800. In the IMR2800, carbon monoxide (CO) was determined by a non-dispersive infrared (NDIR) analyzer with the ranges of 0−20 vol %, 0.01% resolution, and 4% relative accuracy, while nitrogen oxides (NO_x) were measured by an electro-chemical detector (ECD) with the ranges of 0−5000 ppmV, 1 ppm resolution, and 4% relative accuracy. An automatic stack sampler (AST) was used to collect the particulate matter (PM) on a silicon glass fiber filter. The AST system could automatically tune the pump flow rate to fit the monitored flow rate of exhaust gas from the engine by a set of Pitot tubes. Standard leaking check processes were performed before every sampling day. The PM mass on each filter was determined gravimetrically by a Sartorius ME 5-F electronic analytical microbalance with an accuracy of 0.01 mg. The emission factor of each pollutant were then calculated by the following equation:

$$C_P V_S / P_S t \tag{1}$$

where C_P, V_S, P_S, and t represent the concentration of each pollutant, sample volume, power generated during sampling time, and sampling time, respectively. Additionally, all of the tested fuels have three replicated samples, which were taken in 3 successive days, representing that the low relative standard deviation (RSD) of each fuel sample group could also support day−day repeatability.

2.4. PAH Sampling and Analysis. The sampling and analyses of PAHs followed the A730.70C method proposed by the National Institute of Environmental Analysis (NIEA) in Taiwan. A gas chromatograph/mass spectrometer was employed to qualify and quantify the 21 individual PAH levels in the exhaust gas. Both the particulate- and gas-phase PAHs were collected 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. The cleaned filters were stored in a desiccator for at least 8 h to maintain the humidity before and after sampling. The net mass of particles was then determined by mass subtracting the final filter from the initial one. Gas-phase PAHs were collected in three-stage glass cartridges in preliminary sampling work. The results showed the mass of 21 individual PAHs in the third stage were 0.1−2.8% of the total three stages. Thus, two-stage glass cartridges were used to collect the gaseous PAHs in this study. Each cartridge was 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 these two PUF pieces to prevent the leaking of resin during the sampling and extraction processes. The new cartridges were pretreated in a Soxhlet extractor for 24 h with methanol, dichloromethane, and *n*-hexane for a total of 3 days, and then the cartridges were placed in a vacuum oven for 6 h to remove the residual solvents. Each glass fiber filter and packed cartridge was transported to and from the field in an aluminum foil cover to avoid the photo-dissociation of PAHs.

Particulate or gaseous PAH samples were extracted with Soxhlet extractors for 24 h, using an *n*-hexane/dichloromethane mixed solvent of 1:1 volume ratio. The total solvent volumes used were 250 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 cleanup process. The eluents from the silica-packed column cleanup process were reconcentrated to exactly 1 mL in vials. The PAH contents were determined with a gas chromatograph (GC, Agilent 6890N) with a mass spectrometer detector (MSD, Agilent 5973N), which was controlled by a computer workstation (Acer Aspire C500). This GC/MSD was equipped with a capillary column (HP Ultra 2, 50 m × 0.32 mm × 0.17 mm) and an automatic sampler (Agilent 7683 series) and operated under the following conditions: injection volume of 1 μL, splitless injection at 310 °C, ion source temperature at 230 °C, and oven temperature from 50 to 100 °C at 20 °C min^{-1}, from 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 using the scan mode for pure PAH standards. The PAHs were quantified using the selective ion monitoring (SIM) mode. The detection limit (DL) estimated by a serial-diluted standard solution of 21 PAHs was 71−936 pg. The limit of quantification (LOQ) is defined as the DL divided by the sampling volume and was 0.118−1.56 ng m^{-3} for individual PAH compounds in the current study. Seven consecutive injections of a PAH standard yielded RSDs between 4.60 and 8.24% of the GC/MSD integration area. The R^2 of calibration lines in the 21 PAH compounds ranged from 0.995 to 0.999. Additionally, the experimental results showed that the average recovery ($n = 3$) of individual PAHs by NIEA A730.70C was 83−112%. Analyses of field blanks, including glass-fiber filters and cartridges, indicated no significant PAH level (GC/MSD integrated area less than DL).

According to the molecular weight, the 21 individual PAHs were divided into three categories: low molecular weights (LM PAHs containing two- and three-ring PAHs), mid 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 diesel engine generator exhaust was the sum of the 21 individual PAHs. The toxicity of total PAHs was defined as total BaP_{eq}, which is the sum of each individual PAH concentration multiplied by its toxicity equivalent factor (TEF).

3. Results and Discussion

3.1. Fuel Stability. Preliminary tests showed that pure acetone is dissolvable by diesel in any ratio; however, the blended fuel separated into two phases when more than 5 wt % water-contained acetone (WA) was added into a diesel without stabilizers. Both neat soybean oil (S) and isopropyl
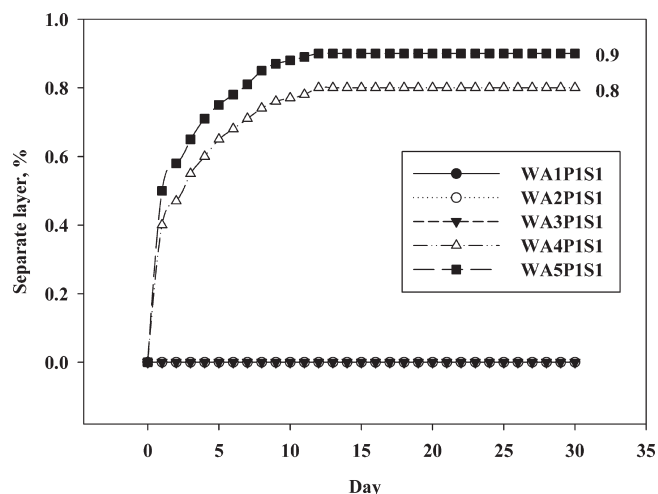
Figure 3. Separate layers of diesel blends in a 30 day standing stability test.

Table 3. BSFC (mL kW^{-1} h^{-1}) of Diesel Blends at Various Engine Loads

BSFC (mL kW^{-1} h^{-1})	1.6 kW		3.2 kW	
	mean ($n = 3$)	RSD (%)	mean ($n = 3$)	RSD (%)
regular diesel	674	0.70	492	0.90
S1	647	0.60	484	0.50
B1	626	0.20	473	0.20
WA1P1S1	666	2.50	497	1.00
WA2P1S1	657	1.60	492	0.90
WA3P1S1	637	1.70	485	0.40
WA1P1B1	661	1.10	472	1.00
WA2P1B1	641	1.10	471	0.90
WA3P1B1	626	0.60	471	0.60
AC1P1S1	658	6.80	471	0.10
AC2P1S1	654	0.40	469	0.10
AC3P1S1	643	0.30	469	0.10
AC1P1B1	642	1.00	471	0.10
AC2P1B1	642	1.20	463	0.60
AC3P1B1	641	0.40	459	3.60

alcohol (P) were used as 1 wt % to stabilize the blended diesel. After a 30 day standing period, three kinds of blended diesels, namely, WA1P1S1, WA2P1S1, and WA3P1S1, all had clear and stable appearances (Figure 3). These stable blends were due to the fact that the neat soybean oil increases the viscosity to retard the separation of water-contained acetone with a regular diesel. In addition, the isopropyl alcohol also acted as a co-solvent, providing an appropriate polarity environment for blending water, acetone, neat soybean oil, and diesel to a perfectly stable condition.

However, after a 12 day standing period, WA4P1S1 and WA5P1S1 transformed from a one-phase liquid crystalline state to a two-phase liquid crystalline state (Figures 1 and 3). These results indicated that the blended diesels have too much water and the fuel stabilities tend to reduce when the fractions of water-contained acetone (WA) are over 3 wt % (for example, WA4P1S1 and WA5P1S1). This is similar to the results seen in other dieselhol studies by Kwanchareon et al.[17] and Chotwichien et al.[20] In addition, the separated layers of WA4P1S1 and WA5P1S1 increased from 0 to 0.8 and 0.9%, respectively, over time and became stable after day 12 (Figure 3).

Furthermore, after the centrifugal test, WA4P1S1 and WA5P1S1 were turned into two-phase clear liquids with 1.0 and 1.2% separate layers, respectively. Therefore, increasing the storage time for these blended diesels will disturb fuel homogeneity, break their stability, change the stable one-phase clear liquid state into a one-phase crystalline one, and finally become two-phase clear liquids.

During fuel-blending processes, the order of adding P and S into a regular diesel is a critical issue. The blended fuels became one-phase crystalline by adding P and S before the mixing process for the final blended diesel. These unstable one-phase crystalline blends might be due to the transesterification reaction between P and S, which produces undissolvable glycerol in diesel and breaks the stability of the blended fuel. Thus, in the first step of the blending processes, the acetone and isopropyl alcohol have to be completely mixed with diesel; second, the neat soybean oil can be added; and finally, the blended diesel is well-mixed.

Additionally, pure acetone (AC) and soybean biodiesel (B) were also added to the regular diesel for comparisons to the

blends containing WA and S, as shown in Table 1. The results of centrifugal testing showed that the pure acetone with 1, 2, and 3 wt %, respectively, being added to the regular diesel with 1 wt % of isopropyl alcohol and 1 wt % of soybean biodiesel were highly stable blended fuels, such as AC1P1B1, AC2P1B1, and AC3P1B1. Additionally, WA3P1B1 is a one-phase clear liquid, which shows that the combination of B and P can stabilize the water-containing acetone (WA) in the regular diesel as well. After both gravitational and centrifugal tests, a total of 15 kinds of stable blended diesels (Table 1) were used in further tests using a DFEG.

3.2. Engine Performance. BSFC (mL kW^{-1} h^{-1}) is widely used to represent engine performance, while a more efficient engine has a lower BSFC.[7,12,17,20,21] At 1.6 kW engine load, when the WA fractions increased from 1 to 2 and 3%, the BSFC decreased by 1.4 and 4.4%, respectively. With regard to a 3.2 kW engine load, when the WA fractions increased from 1 to 2 and 3%, the BSFC decreased by 1.0 and 2.4%, respectively. Therefore, a small amount of neat soybean oil addition in blended diesel did not hinder the combustion efficiency. In addition, as the WA fractions increased from 1 to 2 or 3%, it elevated the combustion efficiency and reduced BSFC.

For blended diesel WA3P1S1, the BSFC at 1.6 and 3.2 kW engine loads was 637 and 485 mL kW^{-1} h^{-1}, respectively, representing 5.5 and 1.4% reductions, respectively, when compared to regular diesel (Table 3). In theory, the BSFC should be correlated with the gross heating values of the regular diesel (41.7 MJ kg^{-1}) and WA3P1S1 (41.1 MJ kg^{-1}) fuel and is thus expected to increase by 1.44% [(41.7−41.1)/41.7] for WA3P1S1, which is in conflict with the above results. Specifically, Di et al.[22] indicated that an excessively oxygenated fuel may reduce its heating value and increase its BSFC. However, the above experimental results indicate that the increase in oxygenated additive (WA) did not either substantially lower the heating values or hinder the combustion but did provide more fuel-containing oxygen and, thus, results in more complete combustion and a lower BSFC.

In comparison to regular diesel, the BSFCs of blended diesel S1 and B1 were reduced by 4.0 and 7.1%, respectively, at 1.6 kW load and were also decreased by 1.6 and 3.9%

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at 3.2 kW load. These results reveal that blended diesel with a higher oxygen density (B1 > S1 > regular diesel) leads to a better energy performance. Similarly, the blended diesel WA3P1B1 has a 1.8 and 3.0% lower BSFC than those of WA3P1S1. Even though adding soybean biodiesel will lead to better engine performance than adding neat soybean oil, the extra cost and waste in the transesterification process will hinder the acceptance of using biodiesel as an additive. Consequently, WA3P1S1 is a good alternative blended diesel fuel with a lower BSFC and cleaner production process than a regular diesel.

To investigate the effect of water content in WA, the BSFCs of water-containing blended diesels (WA3P1S1 and WA3P1B1) were compared to those of pure acetone-containing ones (AC3P1S1 and AC3P1B1). At 1.6 kW engine load, WA3P1S1 and WA3P1B1 had 0.9 and 2.3% lower BSFCs than AC3P1S1 and AC3P1B1, respectively; however, at 3.2 kW engine load, the former two WA-containing blended diesels had higher BSFCs than the latter two AC-containing ones, by 3.4 and 2.6%, respectively. Therefore, the small amount of water in blended diesels did not obviously restrain the combustion reaction at mid-load, while the reductions in fuel heating values affected the engine performance at high load.

3.3. NO$_x$ Emissions. The NO$_x$ emissions increased along with the increasing engine load. In comparison to a regular diesel, the NO$_x$ emissions were reduced with increasing additive ratios at various engine loads, and WA3P1S1 decreased them significantly by 13.6, 7.9, and 6.7% at idling and 1.6 and 3.2 kW loads, respectively (Figure 4a). The NO$_x$ emissions are generally formed by fuel nitrogen conversion, thermal activation, and a prompt (fuel-rich) pathway. In this study, the difference in fuel nitrogen content between regular diesel and WA3P1S1 is not significant. In addition, the prompt NO$_x$ formation is applied in fuel-rich combustion that is in an equivalent ratio higher than 1, such as surface burners, staged combustion systems, and gas turbines,[23] instead of the internal combustors operated at approximately stoichiometric conditions. The thermal mechanism, also called the Zeldovich mechanism, thus dominates the NO$_x$ formation, because the combustion temperature is strictly affected by the fuel. The acetone, isopropyl alcohol, and neat soybean oil have low cetane numbers and heating values. It is known that a low cetane number causes an ignition delay and accumulates the fuel−air mixture before combustion. Thus, a relatively large flow of heat will be released at the beginning of combustion, which leads to a high peak temperature that induces the Zeldovich phenomenon.[24] However, the lower heating value of additives and the latent heat of water contained in acetone may induce a cooling effect. The result of the above two competitive effects can be seen in the exhaust temperature, as shown in Figure 5. The exhaust temperatures decreased with the increasing WA addition; notably, those for WA3P1S1 are reduced by 6.5, 2.4, and 4.7% from a regular diesel at three loads, respectively, and further inhibited the thermal NO$_x$ formation.

It is worth noting that the 1 wt % WA addition resulted in a 0.9% increase in NO$_x$ at idling operation (Figure 4a). Oxygenated additives, such as biodiesel, have been reported
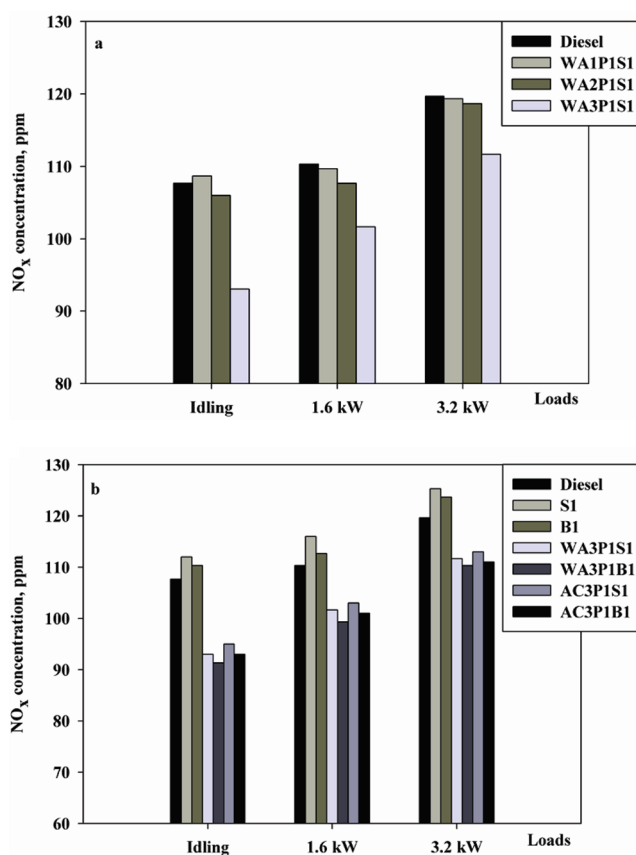

Figure 4. (a and b) NO$_x$ emissions using different diesel blends at various engine loads.
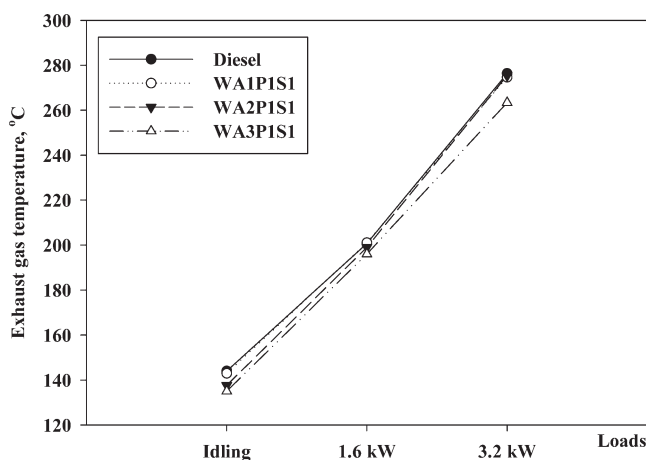
Figure 5. Exhaust temperature at various engine loads.

to slightly increase NO$_x$ emission at low additive fractions because more oxygen was provided to form NO$_x$, while the reductions in heating values were not found to be effective in reducing the thermal NO$_x$ formation.[24,25] To inhibit the NO$_x$ emissions, a 3 wt % additive fraction of WA is more desirable. Additionally, NO$_x$ emission levels of B1 had a 1.5, 2.9, and 1.3% reduction from S1 at idling and 1.6 and 3.2 kW loads, respectively. With regard to replacing the 1 wt % of neat soybean oil with soybean biodiesel in W3P1S1, the NO$_x$ emissions were reduced by 1.8, 2.3, and 1.2% at the

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three loads, respectively (Figure 4b). These reductions again demonstrate that the cooling effect of a lower heating value (biodiesel) may inhibit NO_x emissions. To investigate the cooling effect by water content, the NO_x levels of WA3P1S1 and AC3P1S1 were compared in this study. The results show 2.2, 1.3, and 1.2% increases in NO_x emissions after alternating 3 wt % of WA by AC at various engine loads, respectively (Figure 4b). Therefore, a small amount of water content in acetone can slightly inhibit the NO_x formation.

3.4. PM Emissions. The harmful effects of PM on the respiratory system have been widely investigated, especially with regard to fine particles. Generally, PM emissions are formed by the nucleation (10−100 nm), accumulation/condensation (0.1−1 μm), and coalescence and agglomeration (1−10 μm) processes. Maricq et al.[26] and Vogt et al.[27] showed that the accumulation mode is the major pathway to increase particle mass in the exhaust of diesel engines, which usually occurs through incomplete combustion. Figure 6a demonstrates that the PM emission levels decrease with the increasing water-containing acetone additions. The highest WA-containing fuel, WA3P1S1, significantly reduced the PM emissions by 9.6, 14.5, and 33.3% at low (idling), mid (1.6 kW), and high (3.2 kW) engine loads, respectively (Figure 6a). As an oxygenated fuel, WA3P1S1 provided more oxygen to enhance the combustion reaction and, thus, reduce PM emissions.[28] Specifically, the higher oxygen content would change the fuel oxidation pathway to reduce the critical C_2 formation, which would form the PAH precursor (benzene), and further inhibited the nucleation of HM PAHs to form soot.[29] Nevertheless, the highest alternative ratio of regular diesel in W3P1S1 lead to the lowest sulfur content, which tended to decrease the formation of sulfuric acid in the exhaust gases, while sulfuric acid may further form PM by accumulating or condensing on the soot and metallic ash.[30] Scheer et al.[31] indicated that the particles formed by the nucleation mode consist mainly of sulfate. Nevertheless, Hsieh et al.[32] showed that the PM emission decreases with the decreasing sulfur content in the fishing-boat diesel. Therefore, the high oxygen and low sulfur contents in blended diesels tend to reduce PM emissions.

Two popular bio-produced oxygenated additives, neat soybean oil and soybean biodiesel, were both added at 1 wt % in a regular diesel (S1 and B1, respectively) and tested in a diesel engine generator. At all three engine loads, both S1 and B1 showed PM reductions (Figure 6b). Notably, S1 and B1 more significantly reduced PM levels by 27.7 and 30.7%, respectively, at 80% load, which is the normal controlled condition of a generator. Furthermore, while soybean biodiesel (B) was used to replace neat soybean oil (S) in WA-containing blended diesels, the PM emission of WA3P1B1

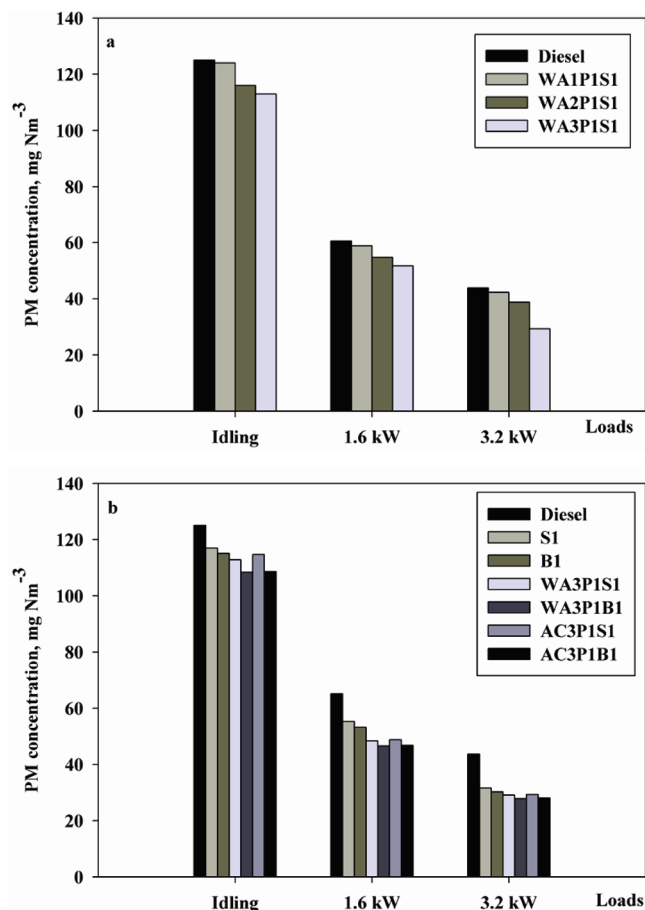**Figure 6.** (a and b) PM emissions using different diesel blends at various engine loads.

decreased to 108, 46.7, and 27.9 mg Nm^{-3}, representing 4.0, 3.6, and 4.3% reductions at each engine load, respectively (Figure 6b). However, as noted earlier, the disadvantages of the transesterification process will discourage the use of soybean biodiesel as an additive. Additionally, PM emissions were not significantly affected using pure acetone (AC) to alter the WA in blended diesels. Consequently, WA3P1S1 is a more cleanly produced blended diesel that produces less PM.

3.5. PAH Emissions. Total PAHs and total BaP_{eq} emission concentrations from a regular diesel and WA3P1S1 are shown in Table 4. The total PAH emissions using WA3P1S1 were 163, 172, and 195 μg Nm^{-3}, representing 14.3, 7.7, and 8.0% reductions from those of a regular diesel, respectively, at idling and mid-, and high-engine loads (Table 4). Several researchers indicated that the aromatic content in a fuel directly affects the PAH levels in the exhaust gas.[33−38] The modification of petroleum diesel by 3% WA, 1% soybean

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Table 4. PAH Emission Concentrations (μg Nm^{-3}) of a Regular Diesel and WA3P1S1 at Various Engine Loads

| | idling | | | | 1.6 kW | | | | 3.2 kW | | | | |
| | diesel | | A3P1S1 | | diesel | | A3P1S1 | | diesel | | A3P1S1 | | |
PAHs	mean	RSD	mean	RSD	mean	RSD	mean	RSD	mean	RSD	mean	RSD	TEF
Nap	53.7	16.5	40.6	12.3	55.2	14.6	49.9	11.1	60.4	11.0	58.0	14.8	0.001
AcPy	4.27	6.03	4.54	0.91	3.49	1.32	3.46	9.94	2.96	2.43	2.61	2.98	0.001
Acp	12.0	16.6	11.6	10.8	11.9	17.4	11.2	19.3	12.3	16.4	11.1	15.6	0.001
Flu	29.4	11.5	25.2	13.1	29.9	20.5	26.0	12.5	49.1	7.75	40.7	12.1	0.001
PA	66.7	11.2	63.8	16.9	68.0	14.0	65.6	14.2	70.2	11.2	66.6	14.2	0.001
Ant	1.73	11.2	1.83	4.9	1.52	9.05	1.48	14.7	1.48	11.5	1.27	11.4	0.010
FL	8.89	17.2	8.55	19.5	8.75	14.4	8.39	11.5	9.00	12.5	8.35	17.8	0.001
Pyr	5.70	6.51	5.62	12.5	5.43	12.0	5.05	20.2	5.70	12.5	5.03	9.65	0.001
CYC	0.03	16.7	0.01	25.3	0.05	10.6	0.05	23.9	0.10	7.68	0.09	10.4	0
B(a)A	0.02	7.44	0.01	45.3	0.04	20.8	0.04	29.6	0.11	21.9	0.09	30.0	0.100
CHR	0.16	30.9	0.13	33.4	0.21	11.5	0.18	27.4	0.26	23.4	0.25	23.9	0.010
B(b)F	0.04	21.8	0.03	41.8	0.05	24.8	0.05	25.8	0.08	15.2	0.08	10.6	0.100
B(k)F	0.08	10.4	0.07	32.1	0.09	20.2	0.08	21.7	0.12	11.6	0.10	15.8	0.100
B(e)P	0.22	33.5	0.18	13.3	0.26	15.1	0.24	17.5	0.32	9.00	0.31	13.5	0
B(a)P	0.02	19.3	0.02	14.7	0.03	8.28	0.03	13.6	0.03	15.4	0.03	19.5	1.000
PER	0.05	11.1	0.05	14.4	0.05	23.9	0.05	18.6	0.07	14.0	0.07	9.04	0
IND	0.02	17.4	0.02	11.5	0.04	16.6	0.03	17.6	0.04	13.3	0.04	10.0	0.100
DBA	0.01	15.7	0.01	22.6	0.01	19.2	0.01	22.6	0.01	5.82	0.01	14.1	1.000
B(b)C	0.36	7.49	0.34	18.0	0.37	15.6	0.36	22.2	0.41	13.6	0.38	12.3	0
B(ghi)P	0.05	11.2	0.04	9.22	0.05	8.00	0.05	8.69	0.06	7.28	0.05	16.8	0.010
COR	0.30	17.2	0.27	16.2	0.31	3.18	0.29	17.4	0.32	11.5	0.31	17.1	0
$\sum$LM PAHs	168	10.5	148	3.78	170	2.10	158	6.08	197	6.14	180	4.42	
$\sum$MM PAHs	14.8	10.9	14.4	15.5	14.5	13.3	13.8	14.4	15.2	11.41	13.9	11.3	
$\sum$HM PAHs	1.10	8.81	0.99	10.29	1.21	8.15	1.14	7.49	1.38	6.91	1.31	6.36	
total PAHs	184	8.78	163	4.31	186	1.94	172	6.71	213	6.46	195	3.52	
total BaP$_{eq}$	0.24	2.00	0.22	1.90	0.26	2.79	0.24	7.04	0.30	4.24	0.28	1.94	

oil, and 1% isopropyl alcohol directly reduces the aromatic contents in diesel fuel and further inhibits PAH emissions.

Notably, the major PAH compound in DFEG emissions was naphthalene (Nap), which contributes 28.4−29.7% and 24.9−29.7% of total PAH mass concentrations from regular diesel and W3P1S1, respectively, at various loads. However, the toxicity of Nap is relatively low (TEF = 0.001) among the PAH homologues. On the other hand, the TEFs of $\sum$HM PAHs, especially BaP (1.0) and DBA (1.0), are much higher than those of $\sum$LM PAHs. Thus, reducing the $\sum$HM PAHs level is a more efficient way to decrease total BaP$_{eq}$ emissions. Using WA3P1S1 specifically leads to a decrease of 12.0, 7.2, and 8.3% $\sum$LM PAHs, 3.3, 5.3, and 8.8% $\sum$MM PAHs, and 9.7, 6.1, and 5.5% $\sum$HM PAHs at three engine loads, respectively. In addition, it emitted 19.4, 26.4, and 31.2 ng Nm^{-3} BaP and 9.3, 10.6, and 12.1 ng Nm^{-3} DBA at three operation loads, respectively (Table 4), with 11.4, 10.0, and 3.5% lower BaP and 13.0, 9.7, and 14.7% lower DBA at each load. Therefore, the significant reductions of high TEF compounds led to 11.4, 7.5, and 8.4% reductions in total BaP$_{eq}$. PAHs are generally expected to form in relative fuel-rich combustion and reduce when more oxygen is present.[39] WA3P1S1 in this study provides more fuel oxygen to reduce the critical C_2H_2 and benzene (C_6H_6) formations and further inhibit the LM PAHs production by polymerization of C_6H_6. Additionally, the existing PAHs were more easily oxidized in such an oxidative condition and, thus, reduced the total PAH concentrations.[29] Nevertheless, the reduction of PM using WA3P1S1 inhibits the adsorption of highly toxic $\sum$HM PAHs and further decreases the total BaP$_{eq}$ in DFEG exhaust.[40]

3.6. CO Emissions. CO is the product of incomplete combustion. Table 5 shows the CO emissions of diesel blends and a regular diesel. The CO emissions decreased significantly with increasing engine loads, because the higher combustion temperature enhanced the combustion reaction at a higher engine load. The CO emission increased with increasing WA ratios and reached the maximum level using WA3P1S1, which increased 45.7, 51.2, and 31.6% at idling and 1.6 and 3.2 kW engine loads, respectively (Table 5), compared to that of a regular diesel. Because acetone, isopropyl alcohol, and soybean oil are all oxygenated species, which should lead to more complete combustion, the above conflicting results should be affected by other factors. Combustions of fuels with oxygenated additives were constrained by several factors. First, the high oxygen content in a fuel reduces its gross heating value, which may lower the combustion temperature and further retard the oxidation reaction. Second, the higher latent heat of additives may directly reduce the flame temperature. Third, the water content in acetone would consume extra heat to evaporate. All three of these factors lead to a cooling effect and to the formation of a greater amount of CO formation.

Using both S1 and B1 resulted in lower CO emissions than those of regular diesel at various engine loads. This result indicates that the fuel oxygen can improve the oxidation reaction. However, the CO emissions became significantly higher after WA or pure acetone was added into diesel blends (Table 5) and lowered their heating values. In addition, the CO emissions from WA3P1B1 were 3.1, 4.3, and 16.7% higher than those with WA3P1S1 (Table 5), which has a higher heating value. Consequently, the oxygenated additives promoted combustion at low additive fractions, but the cooling effect increased the CO emissions with increasing amounts of additives with a low heating value. However, when 3 wt % WA or AC was added , the increased CO concentrations (204−267 ppm) were much lower than the regulated standard for stationary sources (2000 ppm) in Taiwan and were easily removed by current catalytic converters.

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Table 5. CO Emissions Using Different Diesel Blends at Various Engine Loads

	idling		1.6 kW		3.2 kW	
CO (ppm)	mean (*n* = 3)	RSD (%)	mean (*n* = 3)	RSD (%)	mean (*n* = 3)	RSD (%)
regular diesel	197	5.1	168	1.6	155	6.5
S1	187	1.2	152	1.1	144	1.3
B1	190	0.8	159	1.3	150	1.0
WA1P1S1	206	1.5	169	1.5	157	1.9
WA2P1S1	265	2.7	248	7.1	185	3.8
WA3P1S1	287	3.3	254	3.6	204	4.7
WA1P1B1	226	1.4	188	1.6	171	1.2
WA2P1B1	280	1.6	254	1.4	204	1.5
WA3P1B1	296	1.4	265	2.1	238	3.0
AC1P1S1	206	0.7	168	0.3	158	1.0
AP2P1S1	267	0.4	249	0.5	186	0.5
AC3P1S1	288	0.5	254	0.4	204	0.8
AC1P1B1	227	0.5	188	1.1	172	0.9
AC2P1B1	281	0.5	255	0.6	205	1.0
AC3P1B1	297	0.2	267	0.2	240	0.4

Table 6. Emission Factors of PM, CO, NO$_x$, SO$_2$, Total PAHs, and Total BaP$_{eq}$ (Mass kW^{-1} h^{-1})^a

fuels	unit	diesel (*n* = 3)		WA3P1S1 (*n* = 3)		increase (%)		Euro standards		U.S. EPA standards	TWEPA standards
engine loads	kW	1.6	3.2	1.6	3.2	1.6	3.2	2008	2013	2010	2012
EF$_{PM}$	mg kW^{-1} h^{-1}	18.3	10.8	14.3	7.73	−21.9	−28.4	20	10	10	10
EF$_{CO}$	g kW^{-1} h^{-1}	5.62	3.62	7.83	5.49	39.3	51.7	1.5	1.5		10
EF$_{NO_x}$	g kW^{-1} h^{-1}	4.31	2.99	2.69	2.55	−37.6	−14.7	2.0	0.4	0.2	0.2
EF$_{total\ PAHs}$	μg kW^{-1} h^{-1}	28.4	26.9	25.0	23.9	−12.2	−11.0				
EF$_{total\ BaP_{eq}}$	ng kW^{-1} h^{-1}	39.7	37.3	35.5	34.1	−10.5	−8.77				

^{a} Euro, European emission regulations; U.S. EPA, United States Environmental Protection Agency; TWEPA, Taiwan Environmental Protection Agency.

3.7. Emission Factors. According to the above emission results, WA3P1S1 is the most favorable blended diesel in this study. In Table 6, the emission factors of regulated pollutants and PAHs using WA3P1S1 were compared to those using a regular diesel. From the estimation by unit output power (kW h), EF$_{NO_x}$ and EF$_{PM}$ were 2.69 g L^{-1} fuel and 14.3 mg L^{-1} fuel (Table 6), i.e., 37.6 and 21.9% reductions compared to regular diesel at 80% engine load (3.2 kW), which is the normal long-time operating condition of a DFEG. On the other hand, EF$_{CO}$ increased 51.7% at the same operating condition. Shi et al.[16] reported opposite trends of NO$_x$ and CO emissions to current research by adding more oxygenated additives, while the NO$_x$ (4−5 g of NO$_x$ kW^{-1} h^{-1}) and CO (5−7 g of NO$_x$ kW^{-1} h^{-1}) emission factors of base diesel fuel was close to that in this study. The different NO$_x$ emissions might be caused by the relatively higher additive fraction that sharply increased the cetane index and further extended the ignition delay, which finally resulted in a higher NO$_x$ emission in former research. The high additive ratios would also provide a highly lean condition and reduced the CO remaining. In comparison to the research by Shi et al., the PM emissions have the same tendency to reduce with increasing oxygenates. In addition, EF$_{total\ PAHs}$ and EF$_{total\ BaP_{eq}}$ decreased 12.2 and 10.5%, respectively, at 3.2 kW load. In reference to Euro V (2008), Euro VI (2013), United States Environmental Protection Agency (U.S. EPA) (2010), and Taiwan Environmental Protection Agency (TWEPA) (2012), the PM and NO$_x$ emission limits become more stringent (Table 6). Both EF$_{PM}$ and EF$_{NO_x}$ using base PDF in the non-catalyst engine in the current study were over the regulated standards, meaning that the end-of-pipe air pollution control devices (APCDs) had to be installed. Thus, the significant reductions of PM and NO$_x$ would lower the loading and increase the life of APCDs.

3.8. CO$_2$ Reduction. CO$_2$ is the final product of complete combustion of all organic fuels, and it is also one of the most significant GHGs. According to the fuel emission factors (EFs) defined by the Intergovernmental Panel on Climate Change (IPCC), CO$_2$ emissions are proportional to the consumption of fuel. In this study, the EF$_{CO_2}$ of APS blends was compared to that of a regular diesel using a rough estimation, as shown in Figure 7. Case I is the formation and transportation of the APS diesel blends using petroleum acetone and isopropyl alcohol. Capello et al.[41] undertook a comprehensive environmental assessment of petrochemical solvent production. The energy demands of producing acetone and isopropyl alcohol by petrochemical processes are 75 and 62 MJ kg^{-1}, respectively. Assuming that the heat is provided by combusting heavy fuel oil, which is considered to emit 0.076 kg of CO$_2$ for each MJ heat produced, the EF$_{CO_2}$ of petro-acetone and petro-isopropyl alcohol was then calculated as 5.7 and 4.7 kg of CO$_2$ kg^{-1} of product, respectively. Case II examines the use of industrial recycled acetone and isopropyl alcohol to form the APS diesel blends. Figure 8 illustrates a simple distillation system to recycle the acetone and isopropyl alcohol from a solvent-containing wastewater. The major energy-consuming units in this system are one feed pump (A), four reflux pumps (B−E), two condensers, and two distillation column heaters. The total energy consumption rate is calculated by summarizing each unit, and the mass conservation is used to roughly calculate the production rate.[42] The energy consumption per product, acetone or isopropyl alcohol, can thus be calculated as the ratio of the two aforementioned results. The heavy fuel oil

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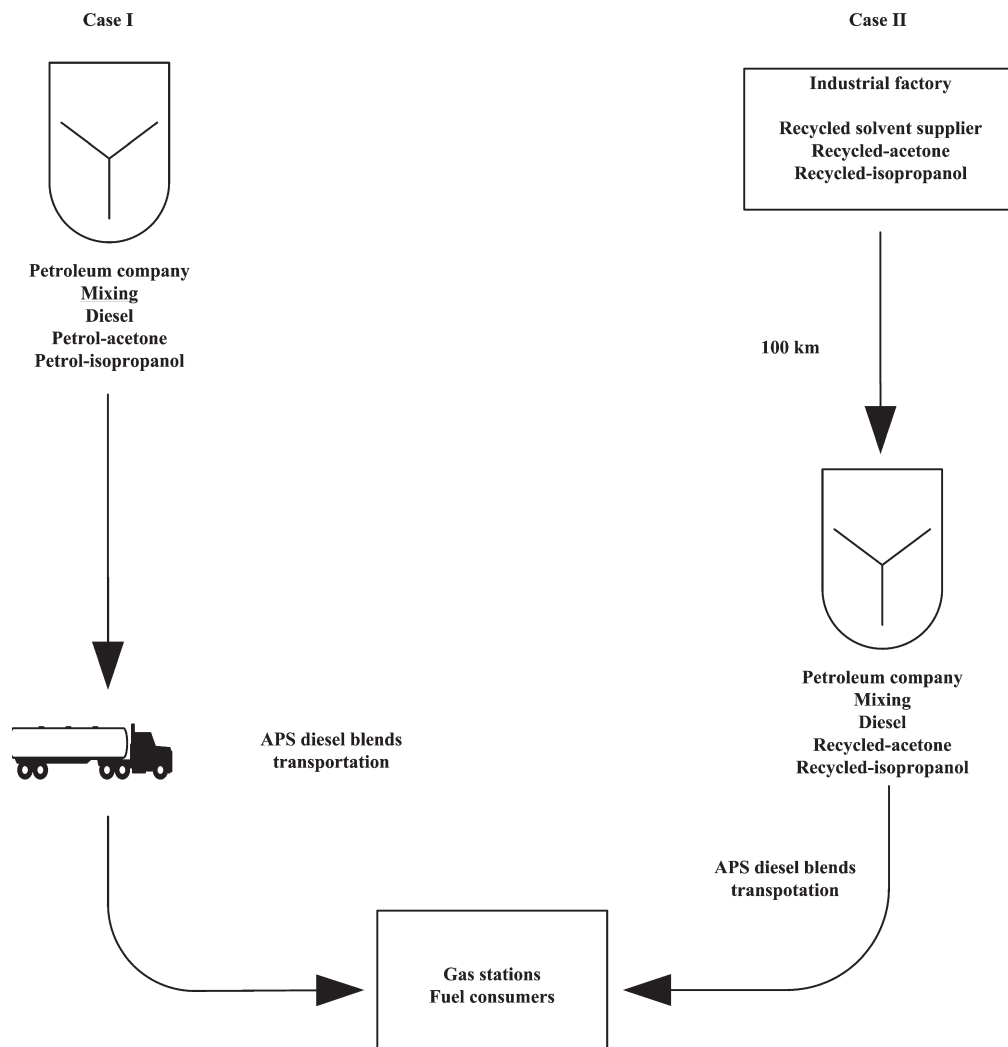
Case I

Case II

Industrial factory

Recycled solvent supplier
Recycled-acetone
Recycled-isopropanol

Petroleum company
Mixing
Diesel
Petrol-acetone
Petrol-isopropanol

100 km

Petroleum company
Mixing
Diesel
Recycled-acetone
Recycled-isopropanol

APS diesel blends
transportation

APS diesel blends
transpotation

Gas stations
Fuel consumers

Figure 7. Production processes of APS diesel blends.

Product: 99 wt.% acetone
Acetone   247.5 kg/hr
Water and IPA   2.5 kg/hr

Condenser

Product: 87 wt.% IPA
IPA   215 kg/hr
Water   32.5 kg/hr

Condenser

Feed:
Acetone   250 kg/hr
IPA   250 kg/hr
Water   500 kg/hr

Pump D
1 hp

Pump E
1 hp

Pump A
2 hp

A

Reflux from vapor
Acetone   61.9 kg/hr
Water and IPA   0.6 kg/hr

Reflux from bottom flow
IPA   61.9 kg/hr
Water   124.8 kg/hr

B

Reflux from vapor
Acetone   53.75 kg/hr
Water and IPA   8.13 kg/hr

Reflux from bottom flow
Isopropanol   8.75 kg/hr
Water   117 kg/hr

Wastewater
IPA   35 kg/hr
Water   468.5 kg/hr

Pump B
1 hp

Intermediate
Isopropanol   247.5 kg/hr
Water   495 kg/hr
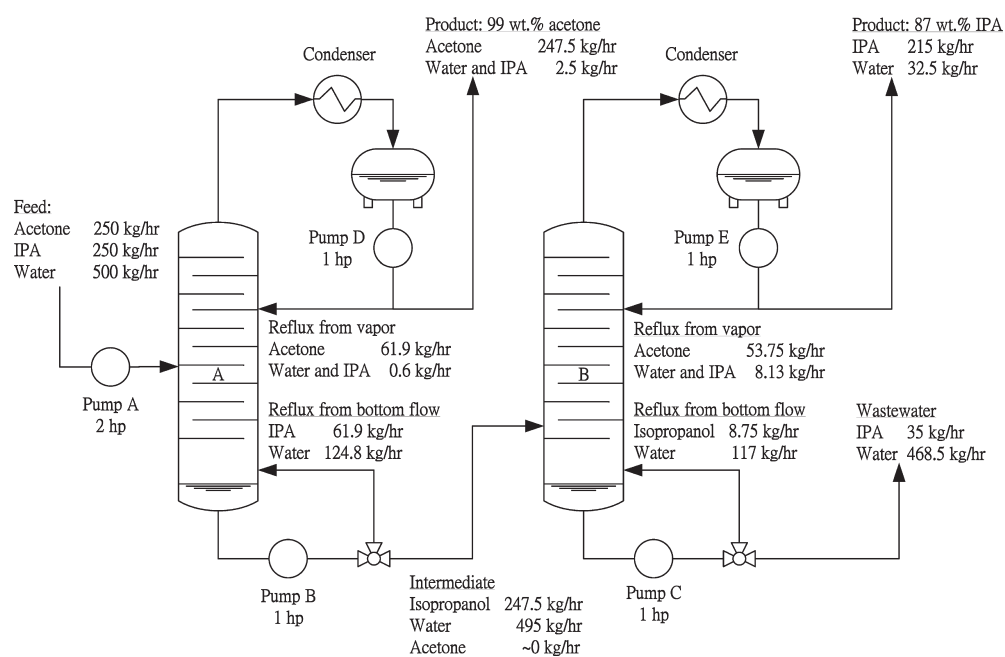Acetone   ~0 kg/hr

Pump C
1 hp

Figure 8. Simple distillation recycling process of acetone and isopropyl alcohol.

Table 7. Estimation of CO_2 Emission Per Solvent Recycled by a Simple Distillation Process

items	energy consumed rate (kJ h^{-1})	energy consumed/product (kJ kg^{-1} of product)	fuel consumption per product[a] (kg of fuel kg^{-1} of product)	CO_2 emission per product (kg of CO_2 kg^{-1} of product)
acetone (99 wt %)				
feed pump A (2 hp) × 1	5400	21.6	0.0005	0.0015
reflux pumps (1 hp) × 2	5400	21.6	0.0005	0.0015
condensers × 1	30490	122	0.0027	0.0087
heater of column A		632	0.0141	0.0451
total		797	0.0178	0.0569
isopropyl alcohol (87 wt %)				
feed pump A (2 hp) × 1	5400	21.8	0.0005	0.0016
reflux pumps (1 hp) × 2	5400	21.8	0.0005	0.0016
condensers × 1	30490	123	0.0028	0.0088
heater of column B		1080	0.0241	0.0772
total		1247	0.0278	0.0891

[a] The total energy demand is assumed to be provided by heavy fuel oil, which has a CO_2 emission factor of 2.98 kg of CO_2 kg^{-1} of fuel.
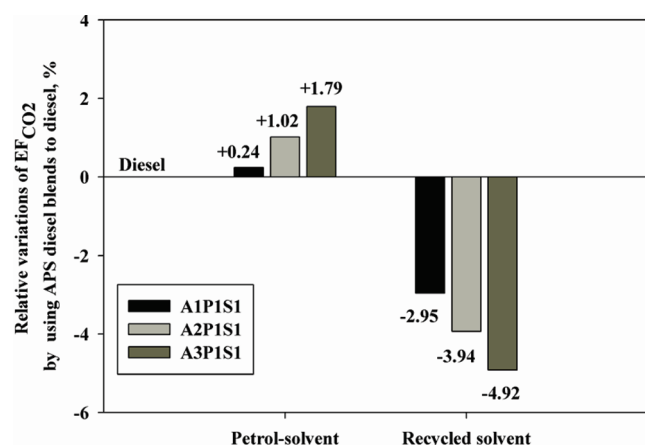

Figure 9. Relative EF_{CO_2} variations from diesel using APS diesel blends.

with the emission factor of 3.20 kg of CO_2 kg^{-1} of fuel is assumed to provide the energy for the recycling system. The CO_2 emissions of recycled acetone and isopropyl alcohol in the current system are then estimated as 0.0569 kg of CO_2 kg^{-1} of acetone and 0.0891 kg of CO_2 kg^{-1} of isopropyl alcohol, respectively (Table 7). Another pathway of CO_2 emission in case II is the collection of recycled solvent. Assume that a 30 ton diesel-fueled tank wagon collects the recycled solvents and is on average driven 100 km from the recycling system to the petroleum company. The regular diesel and solvents are then mixed to form doesel blends. Both regular and blended diesels are further dispersed to gas stations and require another 50 km for transportation. Thus, the transportation EF_{CO_2} of acetone and isopropyl alcohol is 0.00137 kg of CO_2 kg^{-1} of products for both. Additionally, the EF_{CO_2} of neat soybean oil and soybean biodiesel is considered to be 0, because they are known as CO_2-conserved biofuels. Figure 9 shows the relative EF_{CO_2} changes from a regular diesel using the various acetone blends, which are produced from petroleum and recycling processes. In petroleum production processes, the EF_{CO_2} increases with increasing additives, because the CO_2 emissions of petro-acetone and petro-isopropyl alcohol productions are higher than that of a diesel. Petro-WA3P1S1 has the highest CO_2 emission factor by 2.78 kg of CO_2 kg^{-1} of fuel, which is 1.79% higher than that of diesel (2.73). The use of recycled solvents reduces the EF_{CO_2} of APS blends with increasing additives. Recycled WA3P1S1, WA2P1S1, and WA1P1S1 have 4.92, 3.94, and 2.95% lower EF_{CO_2} than that

of diesel because the higher CO_2-emitting diesel is partially alternated by the recycled solvent with lower EF_{CO_2}. According to the statistical results produced by the Ministry of Economic Affairs, Taiwan, the annual regular diesel consumption in Taiwan was 16 283 kL in 2008.[1] Thus, the use of WA3P1S1 produced by case II could reduce the annual CO_2 emissions by 218 590 kilotons. Consequently, WA3P1S1 is a CO_2-reducing and more sustainable diesel blend.

4. Conclusions

(1) The blended diesel WA3P1S1 is a one-phase clear liquid, which shows that the combination of 3% water-contained acetone, 1% isopropyl alcohol, and 1% neat soybean oil can be a stable blended diesel without adding any chemical surfactant. Furthermore, this target fuel exactly simulated a recycling/bio-producing solvent−diesel blend, which stood for a more sustainable purpose than that of pure dieselhol in the former study. (2) For the blended diesel WA3P1S1, the BSFC at 1.6 and 3.2 kW engine loads was 637 and 485 mL kW^{-1} h^{-1}, respectively, i.e., 5.5 and 1.4% less than that of a regular diesel. The little amount of water in blended diesels did not obviously hinder the combustion reaction. (3) The NO_x emissions increased along with the increasing engine load. In comparison to a regular diesel, the NO_x emissions were reduced with increasing additive ratios at various engine loads and WA3P1S1 significantly decreased NO_x emissions by 13.6, 7.9, and 6.7% at idling and 1.6 and 3.2 kW loads, respectively. Therefore, a small amount of water content in the diesel blend can provide a cooling effect and slightly inhibit NO_x formation. (4) PM emission levels decreased as the fraction of water-containing acetone increased. The highest WA-containing fuel, WA3P1S1, significantly reduced the PM emissions by 9.6, 14.5, and 33.3% at low- (idling), mid- (1.6 kW), and high- (3.2 kW) engine loads, respectively. (5) With the addition of water-containing acetone, isopropyl alcohol and neat soybean oil supplied higher oxygen and lower aromatic contents in diesel blend WA3P1S1, promoted the oxidation reactions, and reduced the total PAHs and total BaP_{eq} emissions from diesel engine exhaust by 7.7−14.3 and 7.5−77.4%, respectively. (6) Using the blended diesel WA3P1S1, CO concentrations (204−267 ppm) were much lower than the regulated standard for stationary sources in Taiwan (2000 ppm) and will be easily removed by current catalytic converters. (7) Case II in this study showed that using industrial recycled acetone and isopropyl alcohol to form the WA3P1S1 diesel blends can reduce CO_2 emissions by 4.92%. Consequently, WA3P1S1 is a more sustainable fuel that can reduce both pollution and energy consumption.

This research has successfully simulated the fuel stability and engine performances using water-containing acetone that might be produced by industrial recycling or acetone−butanol−ethanol fermentation processes; however, the compositions of real industrial waste solvent and anti-oxygen fermentation products must be more complicated, which might affect the phase stability and further change the performances in engine operations. This research provides an original idea of water-containing solvent−diesel blends that could be further investigated on multi-component combustions.

Nomenclature

AC = acetone with purity > 99.5%
APS = acetone−(isopropyl alcohol)−soybean oil
AST = automatic stack sampler
B = soybean biodiesel
BaP_{eq} = toxicity equivalence of PAHs
BE = methanol soyate contains 20 vol % ethanol
BMEP = brake mean effective pressure
BSFC = brake-specific fuel consumption
CI = compression ignition
CO = carbon monoxide
CO_2 = carbon dioxide
C_P = concentration of each pollutant
CPC = Chinese Petroleum Corporation
DL = detection limit
ECD = electro-chemical detector
EF_{CO} = emission factor of CO
EF_{CO_2} = emission factor of CO_2
EF_{NO_x} = emission factor of NO_x
EF_{PM} = emission factor of PM (g of PM/L of fuel)
$EF_{total\ BaP_{eq}}$ = emission factor of PM (g of PM/L of fuel)
$EF_{total\ PAHs}$ = emission factor of PM (g of PM/L of fuel)
GC = gas chromatography
GHG = greenhouse gas
HC = hydrocarbon
HDDE = heavy-duty diesel engine
DFEG = diesel-fueled engine generator

IPA = isopropyl alcohol
LOQ = limit of quantification
MSD = mass spectrometer detector
NaOH = sodium hydroxide
NDIR = non-dispersive infrared
NIEA = National Institute of Environmental Analysis
NO_x = nitrous oxides
P = isopropyl alcohol
PAH = polycyclic aromatic hydrocarbon

Acp = acenaphthene
AcPy = acenaphthylene
Ant = anthracene
B(a)A = benzo[*a*]anthracene
B(a)P = benzo[*a*]pyrene
B(b)C = benzo[*b*]chrycene
B(b)F = benzo[*b*]fluoranthene
B(e)P = benzo[*e*]pyrene
B(ghi)P = benzo[*ghi*]perylene
B(k)F = benzo[*k*]fluoranthene
CHR = chrysene
COR = coronene
CYC = cyclopenta[*c,d*]pyrene
DBA = dibenzo[*a,h*]anthracene
FL = fluoranthene
Flu = fluorine
IND = indeno[1,2,3,-*cd*]pyrene
Nap = naphthalene
PA = phenanthrene
PER = perylene
Pyr = pyrene
PDF = premium diesel fuel
PM = particulate matter
$PM_{2.5}$ = particulate matter of 2.5 μm or less
PM_{10} = particulate matter of 10 μm or less
P_S = power generated during sampling time
PUF = polyurethane foam
RSD = relative standard deviation
S = neat soybean oil
SIM = selective ion monitoring
SME = soybean methyl ester
t = sampling time
V_S = sample volume
WA = water-containing acetone