

INVESTIGATION OF COMBUSTION EMISSION OF LIGNITE AND RUBBER WOOD SAWDUST PELLETS USING A TUBE FURNACE

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Abstract

Lignite and rubber wood sawdust generate pollutants under a different criterion, i.e. high bottom ash of lignite and high particulate matter of rubber wood sawdust. Co-pelletizing of lignite and rubber wood sawdust is able to trade the combustion emission, especially the particulate matter. A significance of the particle size distribution of particulate matter and its associated may impact human health and the ambient air. In this study, the influences of the combustion emission of lignite and rubber wood sawdust pellets are investigated through a horizontal tube furnace in a combustion system. The carbon monoxide, particulate matter, polycyclic aromatic hydrocarbons (PAHs), and heavy metals are analyzed using a gas analyzer, an Anderson cascade impactor with inertial filter, a high-performance liquid chromatography coupled to a diode array and fluorescence detectors (HPLC-DAD/FLD), and inductively coupled plasma optical emission spectrometry, respectively. From the results, the 4-6 ring PAHs are considered as the most likely to be carcinogenic to humans with the distribution of fine particles of 0.6 μm . Furthermore, the analysis of PAHs should be made by the combination of detection by the HPLC-DAD/FLD

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to provide qualitative and quantitative analysis. The incomplete combustion emission of carbon monoxide can significantly influence the value of particulate matter and PAHs. Since the pollutants may deposit fine particles, it is suggested that the fine particles are further investigated in detail.

Keywords: Pellets, combustion emission, carbon monoxide, particulate matter, PAHs, heavy metals

Introduction

Coal and lignite are abundant materials for energy resources in Thailand. At present, natural gas is used to generate electricity as well as coal. The alternative options to reduce the expense of natural gas are to use more coal and nuclear resources. Using more coal will reduce the benefit-cost of a carbon price higher than 40 USD/ton but the greenhouse gas emission will increase by 25%. Furthermore, it is estimated that the coal demand in Thailand will rapidly increase by 2030, but that the supply will run out in the near future (Wangjiraniran and Euaarporn, 2010; Wangjiraniran *et al.*, 2013). Coal combustion also generates much higher amounts of bottom ash associated with heavy metals than biomass combustion. In the southern part of Thailand, the rubber tree is a common plant that leads to Thailand being the world leader in natural rubber production and exportation. The rubber wood is generally burnt to produce heat and smoke for rubber sheet drying. It is also used as a main fuel in some industries. During burning, rubber wood produces high amounts of particulate matter and particle-bound polycyclic aromatic hydrocarbons (PAHs) (Furuuchi *et al.*, 2006; Tekasakul and Tekasakul, 2006; Tekasakul *et al.*, 2008). Hence, fuel blending of lignite and rubber wood sawdust should be performed in order to trade the pollutants.

The particulate matter emitted from combustion includes PAHs, heavy metals, flue gas and so on. The PAHs and heavy metals can accumulate with the particulate matter while the flue gas is directly emitted into the atmosphere. They play a major role in the effect on human health through cancer, mutagens, the respiratory system, and mental disorders/diseases. They also cause deaths at a

high concentration (Hata *et al.*, 2014; Nollet, 2005).

Interestingly, the pollutants associated with the particulate matter result in different health outcomes depending on the particle size distribution and degree of toxicity. The fine particles can move deeply into the different regions of the respiratory system by inhalation. The deeper deposit of the particles in the system will cause a greater degree of toxicity even if they have the same compositions (Russell and Brunekreef, 2009; Hata *et al.*, 2014). Furuuchi *et al.* (2006) reported that the combustion of rubber wood emitted a massive concentration of particulate matter at 199 mg/m³. This large contribution to the particulate matter in the workplace was 100 fold higher than the ambient air while the particle-bound PAHs were 10 fold higher than the ambient air. In addition, the particulate matter was majorly distributed in fine particles with a size of less than 0.5 µm. It was mentioned that the environment in the workplace was a critical aspect. Furthermore, Hata *et al.* (2014) reported that the particle-bound PAHs emitted from biomass combustion were abundant in fine particles with a size of less than 0.43 µm, while the particulate matter produced more than 30% of fine particles less than 0.1 µm in size. The solid fuel combustion, including biomass and coal in raw chunks or densified forms, emitted more than 80% of the particles that are less than 2.5 µm (PM_{2.5}), and even the PAHs and heavy metals distributed more than 80% in PM_{2.5} (Shen, 2014; Linak *et al.*, 2000). Therefore, it is necessary to study the characteristics of the combustion emission for the different sizes of the particles.

Determination of emission, especially for the PAHs, is normally made by gas chromatography (GC) or high-performance liquid chromatography (HPLC) (Huang *et al.*, 2013; Nollet, 2005; Zhao *et al.*, 2013). GC is used to analyze the highly volatile PAHs with 7 or fewer aromatic rings with considerably high efficiency. However, the PAHs with lower volatility, i.e. phenanthrene and anthracene, are difficult to quantify by GC. Meanwhile, HPLC is widely used to investigate PAHs because of its ability to separate each component of the PAHs with lower volatility and the higher molecular weight PAHs, easier sample preparation, and greater selection of isomers. HPLC is also able to operate with different detections such as ultraviolet (UV), diode array (DAD), and fluorescence detection (FLD) (Nollet, 2005; Wang *et al.*, 2009; Huang *et al.*, 2013; Zhao *et al.*, 2013). The PAHs' analysis with HPLC is an alternative method, which has been applied in much of the literature (Furuuchi *et al.*, 2006; Tekasakul and Tekasakul, 2006; Tekasakul *et al.*, 2008; Zhao *et al.*, 2013; Hata *et al.*, 2014; Shen, 2014). The analysis is made by separated detection even though the DAD detection is fixed at 254 nm of the wavelength. On the other hand, the DAD detection has less sensitivity and a resolution 4-20 times less than FLD detection (Huang *et al.*, 2013).

Investigation of combustion emission with respect to different particle sizes and detection is an interesting approach in order to control the combustion emission. However, the combustion emission for the co-pelletization of lignite and biomass has not been investigated in detail. The information on co-pelletization combustion is still at an initial stage. According to the description above, combustion emission seriously affects those in the workplace and is a significant source of ambient air pollutants. An understanding of its impact is useful to prevent the deleterious effects on human health and the ambient air.

This present work is aimed at investigating the combustion emission of lignite and rubber wood sawdust pellets relating to particulate matter, PAHs, heavy metals, and carbon monoxide. The emission is sampled through a

horizontal tube furnace in a designed system. The particulate matter, PAHs, and heavy metals are determined in different sizes in a range of 0.07-11 μm while carbon monoxide is examined directly using a gas analyzer. Furthermore, the PAHs are analyzed using HPLC-DAD/FLD, and the relationships of the emission are also discussed. The information of co-pelletization combustion in this study may be essential not only for selecting the type of detection emission analysis but also the emission control during combustion.

Materials and Methods

Materials

The co-pelletized materials were lignite and rubber wood sawdust, which were obtained from Mae Moh, Lampang province and Rattaphum, Songkhla province in Thailand, respectively. The co-pellets were made by using a screw press with 10%wt of starch. The characteristics of the materials and co-pellets are detailed in a previous study (Kan *et al.*, 2016). Three different ratios of lignite-rubber wood sawdust pellets, i.e., 0%, 50%, and 100% were used in these experiments.

Methods

Combustion System

Eleven pellets were randomly selected with a 3.5-4 ratio of length to diameter. The pellets were burnt in the horizontal tube furnace that consists of a quartz tube (OD = 60 mm, ID = 55 mm, and L = 850 mm), as shown in Figure 1. The pellets were placed on ceramic boats and burnt at the center of the heating zone (L = 650 mm) from room temperature to 700°C. The temperature was increased uniformly at 5°C/min. To ensure that all the residue would be burnt out with a slow heating rate, 700°C of heat was held for 20 min. Dry clean air filtered with packs of silica gel and HEPA filters were purged into the furnace at a rate of approximately 1.6 L/min, which was controlled by an orifice meter with a 1 mm diameter connected with a u-tube manometer. The combustion air (1.6 L/min) was purged to obtain complete combustion in terms of the

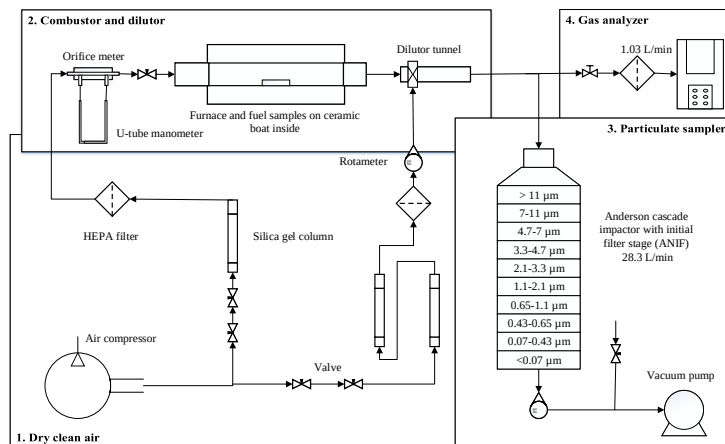


Figure 1. Schematic diagram of combustion system

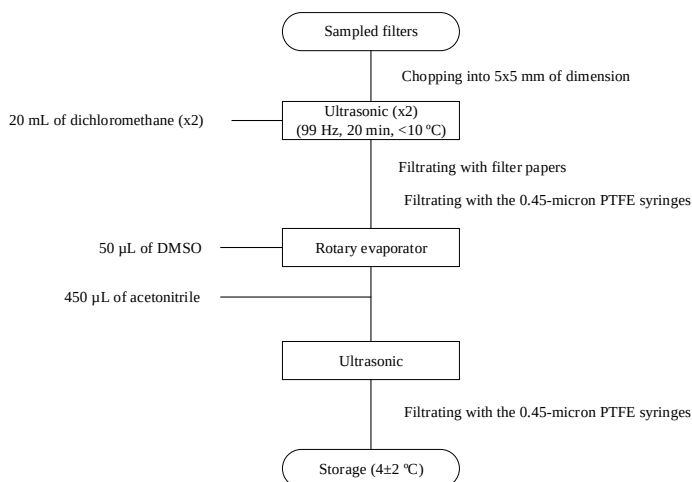


Figure 2. Extraction process of PAHs by ultrasonic extraction technique

stoichiometric air ratio (1.2) which is commonly recommended in a power plant or in a laboratory test to prevent cool combustion and incomplete combustion (Drbal *et al.*, 1996; Mastral *et al.*, 2000). The exhaust from the combustion was diluted by using the dry clean air in the dilutor tunnel in order to minimize the exhaust moisture and temperature. From the dilutor, the particulate matter was sampled by using an Anderson cascade impactor with initial filter stage (ANIF), model Dylec NA200 (Tokyo Dylec Corp., Kyoto, Japan), and the flue gas was examined by a gas analyzer,

model Testo-350XL (Testo SE & Co. KGaA, Lenzkirch, Germany).

Emitted particle sampling and polycyclic aromatic hydrocarbon analysis

The particulate matter was segregated into different size ranges, i.e., >11, 7-11, 4.7-7, 3.3-4.7, 2.1-3.3, 1.1-2.1, 0.65-1.1, 0.43-0.65, 0.07-0.43, and <0.07 μm . The particulate matter was sampled with treated quartz filters ($D = 80 \text{ mm}$, $t = 72 \text{ h}$, $T = 25^\circ\text{C}$, and $\text{RH} = 50 \%$), model Pallflex 2500QAT-UP (Pall Corp., Port Washington, NY, USA).

Table 1. Mobile phases of gradient condition of PAHs analysis

Time (min)	Flow rate (mL/min)	Acetonitrile (%)	Ultra-pure water (%)
0	0.5	70	30
10		70	30
25		90	10
27		99	1
30		100	0
75		100	0
76		70	30
80		70	30

Table 2. Optimum wavelength of PAHs analysis with FLD and DAD detection

Time (min)	DAD detection λ (nm)	FLD detection		PAHs
		λ_{ex} (nm)	λ_{em} (nm)	
0	254	280	340	NAP, ACE, FLU, ACY (ACY no fluorescence)
23		250	400	PHE
29		286	433	ANT, FLA
31		331	392	PYR
34		264	407	BaA, CHR, BbF, BkF BaP, DahA, BghiP
65		294	482	IcdP
72		280	340	-
80		280	340	-

All sampled filters from the ANIF were treated in a lightless desiccator for 72 h and then the components of 16 PAHs were determined, i.e. naphthalene (NAP, 2 rings), acenaphthylene (ACY, 3 rings), fluorene (FLU, 3 rings), acenaphthene (ACE, 3 rings), phenanthrene (PHE, 3 rings), anthracene (ANT, 3 rings), fluoranthene (FLA, 4 rings), pyrene (PYR, 4 rings), benzo(a)anthracene (BaA, 4 rings), chrysene (CHY, 4 rings), benzo(b)fluoranthene (BbF, 5 rings), benzo(k)fluoranthene (BkF, 5 rings), benzo(a)pyrene (BaP, 5 rings), dibenz(a,h)anthracene (DahA, 5 rings), benzo(g,h,i)perylene (BghiP, 6 rings), and indeno(1,2,3-cd)pyrene (IcdP, 6 rings). The PAHs' extraction process was operated by using an ultrasonic extraction technique as illustrated in Figure 2. The filters were cut into small pieces (5×5 mm). The PAHs on the filters were extracted twice for 20 min each time with dichloromethane. Then the extracted solution was filtrated and dimethyl sulfoxide (DMSO) was added.

After that, the solution was evaporated with a rotary evaporator in order to remove the dichloromethane. Lastly, the residues were dissolved with acetonitrile and kept in a refrigerator (4±2°C) for analysis of the PAHs.

The 16 PAHs were analyzed by using high-performance liquid chromatography with coupled to a diode array and fluorescence detection (HPLC-DAD/FLD), Hewlett Packard series 1100 (Hewlett-Packard Co., Palo Alto, CA, USA) along with Inertsil ODS-P column (GL Sciences Inc., Torrance, CA, USA) (D_p = 5 μ m, D = 4.6 mm, L = 250 mm). The mobile phase was a mixture of acetonitrile and ultra-pure water from 70-100% of acetonitrile at 0.5 ml/min (Table 1). The wavelengths of each PAH component were set based on 254 nm of DAD and 280-433 nm of FLD (Table 2).

To obtain the quality control of the PAHs, the 16-PAHs-mix standards were diluted with the acetonitrile in order to prepare the calibration curves and the detection limit. The concentration

Table 3. Concentration of 16-PAHs-mix standard solution and its dilution

N°	PAHs	Ref. Conc. (µg/ml)	STD100	STD200	STD1000	STD5000	STD10000
1	NAP	999.2	9.992	4.996	0.9992	0.19984	0.09992
2	ACY	1984	19.84	9.92	1.984	0.3968	0.1984
3+4	ACE+FLU	1197.2	11.972	5.986	1.1972	0.23944	0.11972
5	PHE	99.4	0.994	0.497	0.0994	0.01988	0.00994
6	ANT	99.1	0.991	0.4955	0.0991	0.01982	0.00991
7	FLA	197	1.97	0.985	0.197	0.0394	0.0197
8	PYR	99	0.99	0.495	0.099	0.0198	0.0099
9	BaA	100.1	1.001	0.5005	0.1001	0.02002	0.01001
10	CHY	99.9	0.999	0.4995	0.0999	0.01998	0.00999
11	BbF	199.2	1.992	0.996	0.1992	0.03984	0.01992
12	BkF	100.1	1.001	0.5005	0.1001	0.02002	0.01001
13	BaP	99.4	0.994	0.497	0.0994	0.01988	0.00994
14	DahA	199.6	1.996	0.998	0.1996	0.03992	0.01996
15	BghiP	192.5	1.925	0.9625	0.1925	0.0385	0.01925
16	IcdP	100	1	0.5	0.1	0.02	0.01

Table 4. Detection limits and percent recovery of 16 PAHs

N°	PAHs	Detection Limit (ng/mL)	Recovery FLD (%)	Recovery DAD (%)
1	NAP	< 49.96	72.71	83.72
2	ACY	< 99.2	-	101.68
3+4	ACE+FLU	< 59.86	72.83	99.79
5	PHE	< 4.97	91.98	60.45
6	ANT	< 4.955	82.04	42.52
7	FLA	< 9.85	98.91	86.07
8	PYR	< 4.95	103.43	110.69
9	BaA	< 5.005	110.80	88.75
10	CHY	< 4.995	113.26	113.28
11	BbF	< 9.96	111.33	116.90
12	BkF	< 5.005	108.56	105.78
13	BaP	< 4.97	123.79	137.86
14	DahA	< 9.98	114.97	124.53
15	BghiP	< 9.625	138.57	106.24
16	IcdP	< 5	104.17	104.89

of the standard solution and the standard calibration curves of the 16 PAHs along with the regression equation are shown in Table 3 and Figure 3, respectively.

Moreover, the limit of detection was the lowest concentration of the PAHs in which the HPLC system's ability to detect in terms of the signal to noise ratio was larger than 3, whereas the recovery indicates the yield pre-concentration or extraction of the analyses (Table 4). In order to get the results of the recovery, the diluted 16-PAHs-mix standards, which were prepared for the calibration curve, were spiked on the blank filters using a micro-pipette. Similar to the filter treatment and PAHs' analysis, the spiked filters were treated in the lightless

desiccator for 72 h and then they were extracted and analyzed by HPLC-DAD/FLD. The percent recovery can be calculated via the equation below:

$$\%R = 100 \times \frac{m_{\text{measure}}}{m_{\text{real}}} \quad (1)$$

where %R is the percent recovery; m_{measure} is the measured concentration of the PAH standard solution; and m_{real} is the real concentration of the PAH standard solution on the spiked blank filters.

The recovery was confirmed to be 72-138% with the standard calibration curves ($R^2 > 0.99$) depending on each component of the

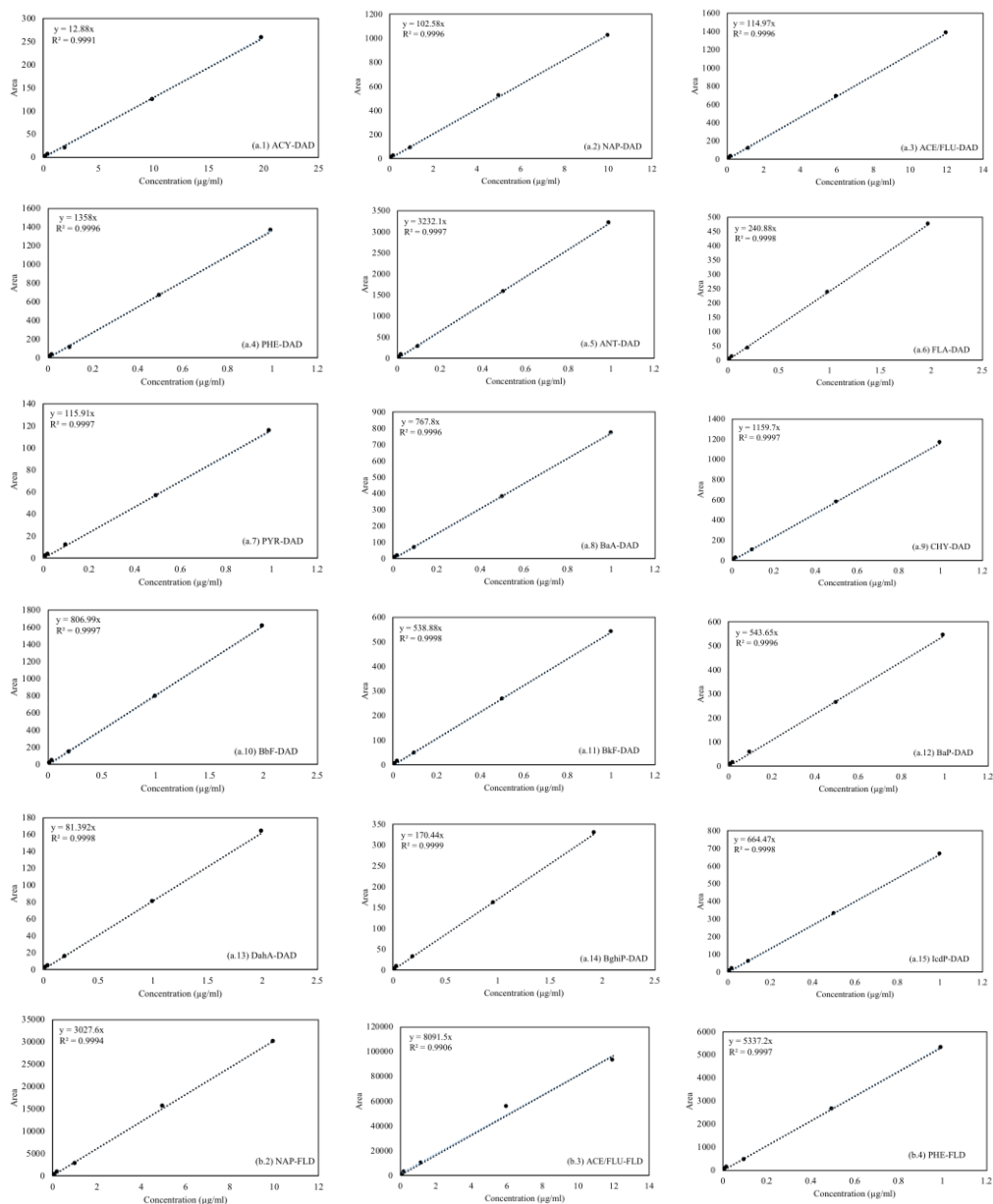


Figure 3. Standard calibration curves of 16 PAHs with (a) DAD detection: (a.1) acenaphthylene, (a.2) naphthalene, (a.3) acenaphthene and fluorene, (a.4) phenanthrene, (a.5) anthracene, (a.6) fluoranthene, (a.7) pyrene, (a.8) benzo(a)anthracene, (a.9) chrysene, (a.10) benzo(b)fluoranthene, (a.11) benzo(k)fluoranthene, (a.12) benzo(a)pyrene, (a.13) dibenz(a,h)anthracene, (a.14) benzo(ghi)perylene, (a.15) indeno(123-cd)pyrene; and with (b) FLD detection: (b.1) naphthalene, (b.2) acenaphthene and fluorene, (b.3) phenanthrene, (b.4) anthracene, (b.5) fluoranthene, (b.6) pyrene, (b.7) benzo(a)anthracene, (b.8) chrysene, (b.9) benzo(b)fluoranthene, (b.10) benzo(k)fluoranthene, (b.11) benzo(a)pyrene, (b.12) dibenz(a,h)anthracene, (b.13) benzo(ghi)perylene, (b.14) indeno(123-cd)pyrene

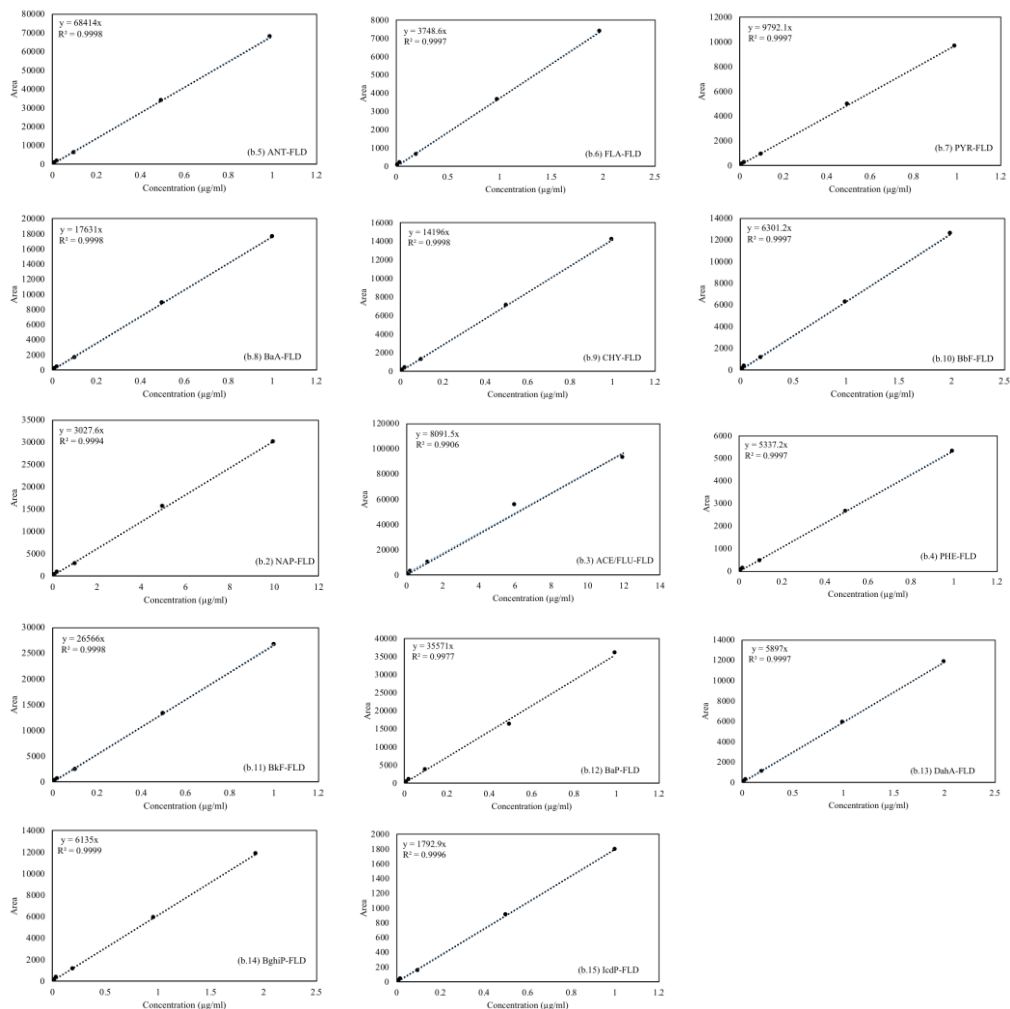


Figure 3. (continuous)

PAHs. Moreover, the values of the PAHs were corrected using subtraction of the values of the PAHs' blanks, which were obtained using blank filters analysis.

Flue Gas Monitored

The flue gas was tested by using a gas analyzer with a constant flow rate of 1.03 L/min. The flue gas was automatically recorded every 2 min in the instrument.

Heavy Metal Analysis

The heavy metals were analyzed by using an inductively coupled plasma optical emission spectrometry (ICP-OES), model Optima 4300 DV (PerkinElmer, Inc., Waltham, MA, USA). The target heavy metals were examined via the optimum wavelengths, i.e., 396.153 nm of Al, 267.716 nm of Cr, 327.393 nm of Cu, 238.204 nm of Fe, 220.353 nm of Pb, and 206.200 nm of Zn. Furthermore, the blank filters were

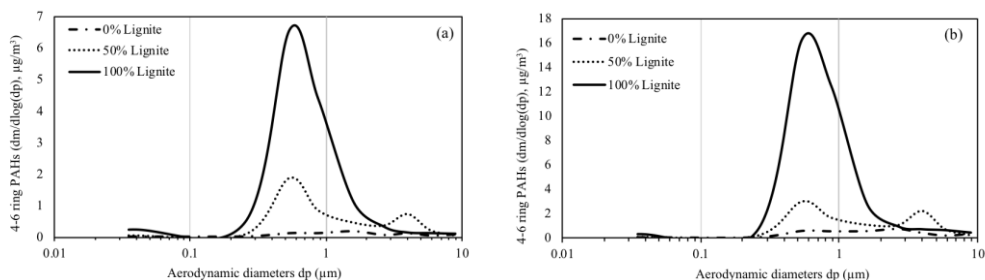


Figure 4. Particle size distribution of 4-6 ring PAHs in different size ranges of particulate matter: (a) fluorescence detection and (b) diode array detection

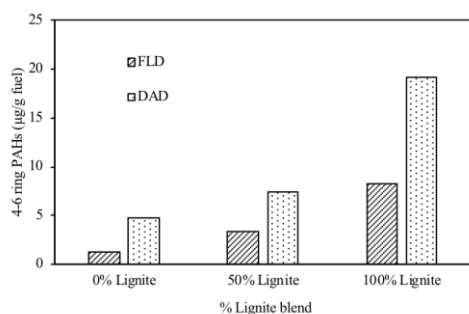


Figure 5. Concentration of 4-6 ring PAHs based on diode array and fluorescence detection

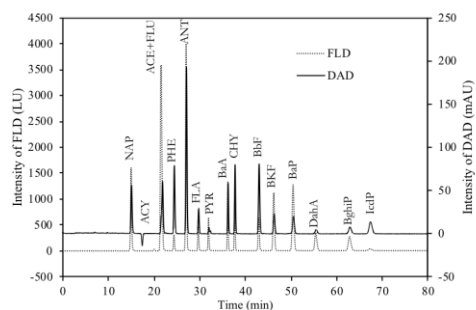


Figure 6. PAHs components based on time versus intensity of fluorescence and diode array detection

prepared in order to correct the values of the heavy metals using subtraction of the values between the heavy metals of the particulate matter and the heavy metals of the blank filters.

Results and Discussion

PAHs Analysis Based on Detection

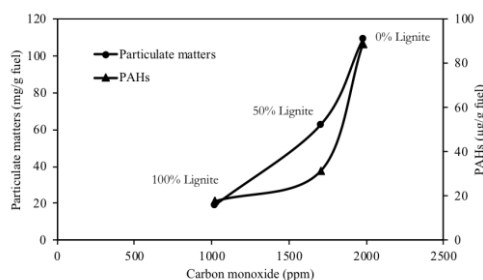
It is believed that 4-6 ring PAHs are the most carcinogenic to humans among the 16 priority PAHs (Tekasakul and Tekasakul, 2006; Bojes and Pope, 2007; Kim *et al.*, 2013). Hence, the 4-6 ring PAHs are taken into account. As seen in Figure 4, the particle size distributions of the 4-6 ring PAHs of the 50% and 100% lignite display bimodal and unimodal behaviors, respectively. On the other hand, the particle size distribution of the 4-6 ring PAHs of the

0% lignite displays an unclear modal behavior because of the lesser concentration of 4-6 ring PAHs. The bimodal behavior of the 50% lignite is caused by the different properties of the lignite and rubber wood sawdust. However, the 4-6 ring PAHs are mostly abundant in the fine particles of 0.6 µm. The PAHs accumulated in the fine particles can go a long distance in the atmosphere and further adversely affect human health by penetrating deeply into the inhalation system. It is suggested that the PAHs accumulated in the fine particles should be critically investigated in a further study similar to the suggestion of Russell and Brunekreef (2009) and Hata *et al.* (2014).

The concentration of 4-6 ring PAHs based on the DAD and FLD detection is shown in Figure 5. The FLD detection presents a good determination, which is in good agreement with the literature (Nollet, 2005; Huang *et al.*,

Table 5. Characteristics of heavy metals in different size range of particulate matter emitted from combustion of 0%, 50%, and 100% lignite pellets (mg/kg particulate matter)

Size (μm)	Cr	Cu	Fe	Pb	Zn	Al
<0.07	<0.47	<0.53	<0.47	<3.26	<0.27	<1.42
0.07-0.43	<0.47	<0.53	<0.47	<3.26	<0.27	<1.42
0.43-0.65	<0.47	<0.53	<0.47	<3.26	<0.27	<1.42
0.65-1.1	<0.47	<0.53	<0.47	<3.26	<0.27	<1.42
1.1-2.1	<0.47	<0.53	<0.47	<3.26	<0.27	<1.42
2.1-3.3	<0.47	<0.53	<0.47	<3.26	<0.27	<1.42
3.3-4.7	<0.47	<0.53	<0.47	<3.26	<0.27	<1.42
4.7-7.0	<0.47	<0.53	<0.47	<3.26	<0.27	<1.42
7.0-11.0	<0.47	<0.53	<0.47	<3.26	<0.27	<1.42
>11.0	<0.47	<0.53	<0.47	<3.26	<0.27	<1.42

**Figure 7. Relationship of carbon monoxide versus particulate matter and total concentration of PAHs**

2013). As compared to the FLD detection, the DAD detection provides a 2 fold greater valuation of the PAHs. The areas, which are proved using the DAD detection, are smaller, so will cause more errors during manual integration of the PAHs' peaks, as shown in the example in Figure 6. All the PAHs' selections are targeted depending on the optimum wavelength and time as well as the value above the limit of detection of 5-59.86 ng/mL. The FLD detection provides selectively optimum excitation and emission wavelengths based on each component of the PAHs in the range from 280-433 nm of the wavelength, while the DAD detection targets all the PAHs' components at 254 nm of the wavelength. Moreover, the FLD detection is more sensitive and has a higher resolution than the DAD detection. However, the FLD detection provides low signals in the components

of the NAP, ACE, and FLU, whereas ACY is not detectable. It is confirmed that the FLD detection is quantified for more accuracy, whereas the DAD detection is qualified for the 16 PAHs (Huang *et al.*, 2013; Zhao *et al.*, 2013). Therefore, determination of the analysis of the 16 priority PAHs is recommended using the combination of DAD and FLD detection.

Emission Results of Particulate Matters, PAHs, and Carbon Monoxide

The carbon monoxide and particulate matter, especially the unburnt carbon in the particulate matter, are the by-products of incomplete combustion while the PAHs are mostly abundant in the particulate matter, so the relationship of the carbon monoxide versus the particulate matter and the total concentration of the PAHs is plotted as shown in Figure 7. From the results, when the value of the carbon monoxide increases, the value of the particulate matter and PAHs will also increase. The 0% lignite pellet burns fast due to its characteristic of highly volatile matter. The reaction leads to a rapid reactivity, where carbon cannot completely oxidize to carbon dioxide in a suitable time. Moreover, the change of temperature in the combustion time can be considered as incomplete combustion. These consequences cause an unstable medium and further produce high carbon monoxide and particulate matter (Akdağ *et al.*, 2016). Meanwhile, the particle-bound PAHs will increase along with an increment in the particulate matter.

Heavy Metals

The characteristics of heavy metals in different size ranges of particulate matter emission from the co-pelletization combustion are shown in Table 5. The target heavy metals such as Cr, Cu, Fe, Pb, Zn, and Al are lower than the limit of detection in the experiment. The limit of detection is examined in the range of 0.27-3.26 mg/kg of particulate matter. There is no doubt about the heavy metals of the 0% lignite when the biomass naturally grows and contributes little or no concentration of heavy metals. However, the lignite blends may influence the heavy metals in the co-pelletization. According to the literature (Yoo *et al.*, 2002; Chang *et al.*, 2004; Bhangare *et al.*, 2011; Zhou *et al.*, 2015), the heavy metals are in the categories of non-volatile (Fe and Al) and semi-volatile heavy metals (Cr, Cu, Pb, and Zn). Hence, the heavy metals may be either deposited in the bottom ash or transported along with the particulate matter. The non-detectable values may be caused by the high limit of quantitation value capable of being detected by the instrument or by the low amount of particulate matter (0.3-23 mg) on the filters. Therefore, it is recommended to either increase the amount of particulate matter or select another elemental analysis technique, especially graphite furnace atomic absorption spectrometry or hydride generation atomic absorption spectrometry, as recommended by Iwashita *et al.* (2007), which is more accurate and selective than ICP-OES. Moreover, the amount of sample required by the atomic absorption spectrometry method is a very small amount and the method is able to detect the target elements down to sub-ppb. However, in this work the sample size is large. Thus, ICP-OES was selected because of its suitability.

However, the co-pelletization of lignite and rubber wood sawdust is able to enhance the concentration of heavy metals by condensing the fine particles or by evaporation due to the high volatile matter of the biomass. It is worth noting that once the heavy metals accumulate in the fine particles, the result will be serious carcinogenic harm to human health by inhalation. Special attention should be paid to this as with the PAHs.

Conclusions

The investigation of combustion emission of lignite and rubber wood sawdust sampled through a horizontal tube furnace and tested in different size ranges of particulate matter and detection found that: (1) the presence of fine particles smaller than 0.6 μm is the critical consideration for the accumulation of 4-6 ring PAHs, which seriously pollute the human respiratory system; (2) the analysis of 16 priority PAHs should be coupled with detection by HPLC-DAD/FLD; and (3) the increment of incomplete combustion emission of carbon monoxide relates to the increment of particulate matter and particle-bound PAHs. The authors suggest that heavy metal analysis on the filters should be made using higher elemental resolution equipment.

Acknowledgments

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