



Effects of Moisture Content and Burning Period on Concentration of Smoke Particles and Particle-Bound Polycyclic Aromatic Hydrocarbons from Rubber-Wood Combustion

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ABSTRACT

Physical and chemical characteristics of particles from rubber-wood combustion in a natural rubber sheet smoking process were studied. Experimental parameters include wood moisture content and wood-burning period. The size distribution of smoke particles was measured by using an 8-stage Andersen air sampler. Total smoke particle concentration was determined by collecting particles using a modified high volume sampler. Polycyclic Aromatic Hydrocarbons (PAHs) were extracted with Benzene-Ethanol by using ultrasonic technique and analyzed by HPLC/UV detection. Results show that the size distribution of smoke particles is single-mode in which the mass median aerodynamic diameter (MMAD) is 0.68 μm and the average smoke concentration is 15.806 mg/m^3 . This is equivalent to a mass emission to workplace of 4.33 $\text{kg}/\text{month}/\text{room}$. The smoke particle concentration and associated PAH concentration clearly depend on the wood moisture content and burning period. The highest PAH concentration and smoke particle concentrations were found to be 60.59 to 118.06 $\mu\text{g}/\text{m}^3$ and 23.35 to 47.54 mg/m^3 , respectively, for a wood moisture content of 37.4 to 73.6% d.b. (dry basis) at the initial period. Smoke particle-bound PAHs are dominated by 4-6 ring PAH compounds that contribute to more than 60% of the total PAHs.

Keywords: Rubber-wood; PAHs; Smoke particle; Moisture content; Burning period.

INTRODUCTION

Natural rubber (*Hevea brasiliensis*) has been used as a major raw material for commercial products including automotive tires, medical gloves, condoms, rubber bands, and flexible tubing (Tekasakul *et al.*, 2006). The raw natural rubber is present in the form of white latex liquid when tapped from the rubber trees. The latex life is as short as one day if not properly preserved (Tekprasit, 2000). Many forms of preserved rubber have been created to extend its shelf life before it is consumed by the production of the products noted above. These forms include ribbed smoked sheet (RSS), block rubber, rubber concentrate latex and others. RSS is one of the most popular forms, however.

In the production of RSS, fuel wood (usually fresh, old rubber-wood) is burned to supply heat (and smoke) to raw rubber sheets in the rubber smoke room. Burning of fresh rubber-wood causes a high concentration of smoke particles. A method to properly control these particles has not been implemented at any levels of the production industry. Some of the smoke may leak into the workplace area of the factory building, directly influencing the health of workers. The smoke particles from wood combustion contain extremely high concentrations of hazardous pollutants, such as polycyclic aromatic hydrocarbons (PAHs) (Hedberg *et al.*, 2002; Venkataraman *et al.*, 2002; Hay *et al.*, 2003; Francisco

et al., 2005; Furuuchi *et al.*, 2006). PAHs are generally unreactive and have low acute toxicities, but degraded and biotransformed products of PAHs can be very potent mutagens and carcinogens (Leo, 2006). PAHs may induce cancer of the lungs, bladder, and skin. Several PAHs have been classified as probable human carcinogens (IARC, 1982) while exposure to high levels of PAHs has been shown to produce immunosuppressive effects (Leo, 2006). Most PAHs are associated with fine airborne particles, typically 0.5 μm or smaller (De martinis *et al.*, 2002; Venkataraman *et al.*, 2002; Saez *et al.*, 2003). Choosong *et al.* (2007) studied the working environment in a rubber sheet smoking factory in Thailand and found that concentrations of particle-bound PAHs were extremely high, particularly in fine particles. The worker's main discomforts were smoke and odor. Upper respiratory symptoms are very likely related to pollutants in the workplace.

The physicochemical properties of the smoke particles from the burning of various kinds of wood were investigated. The variations of smoke and PAH emission were found to depend on the type of fuel and cooking stove used in the combustion process (Oanh *et al.*, 2005), the biomass blending ratio, the excess air ratio and the moisture content of wood used in the combustion process (Chao *et al.*, 2008). However, there is a lack of understanding of certain parameters influencing the emission of particles and associated PAHs from rubber-wood combustion for different wood properties and burning condition.

In this work, characteristics of the emissions from rubber-wood combustion in an RSS cooperative, community-level factory in Thailand, were studied. The characteristics include: concentration, size distribution, and PAH profiles. The effects of

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moisture content of the rubber-wood and wood burning period on smoke particle and PAH emissions are elaborated. Results from this study will be useful for further studies of the impact of emissions from the rubber smoking industry on the workplace and atmospheric environments.

EXPERIMENTAL PROCEDURE

In this section, we explain the methods used to collect and analyze particle and PAH samples from an oven used in an RSS cooperative.

Sampling Methods

Rubber-wood was burnt in an oven of a rubber cooperative. The size of a typical oven is 0.55 m × 0.65 m × 185 m. The wood is usually placed on the floor of the oven when burned. Air is drawn into the oven via a slit in the bottom of the oven door. Source smoke particles in the smoke room are sampled by two sets of equipment to measure the total concentration and the size distribution (Fig. 1).

Total Smoke Concentration

A simple high-volume air sampler was built and used for the measurement of the total smoke particulate concentration. A 110-mm-diameter quartz fiber filter (Advantec, QR-100) was placed in an aluminum filter holder. The smoke particles were introduced to the filter using a 1500-W household vacuum cleaner (Hitachi, CV-T41). The flow rate was controlled at 100 L/min by adjusting a control valve as shown in the top part of Fig. 1. Flow rate was measured by an orifice meter calibrated by a wet gas meter (Shinagawa, W-NKDa-10B) and a corresponding U-tube manometer. Samples were collected at 15, 30, 60, 75, 120, and 135 minutes after the rubber-wood was fed into the oven and each sampling period was 10 minutes. To study the effect of wood moisture content, each piece of wood, 6 to 10 cm in diameter, was dried in an electric oven (Mammert, 400) at 110°C to determine its initial moisture content on a dry basis.

Size Distribution of Smoke Particle

To determine the size distribution of the smoke particles, samples were collected by an 8-stage Andersen sampler (Dylec,

AN200). The impactors have 50% cut-off aerodynamic diameters of 11.0, 7.0, 4.7, 3.3, 2.1, 1.1, 0.65, 0.43 μm for stage 1-8, respectively, and particles smaller than 0.43 μm are collected on a back-up filter. A constant sampling air flow rate of 28.3 L/min was controlled by using a vacuum pump, a control valve, and a rotameter as shown in the bottom part of Fig. 1. Particles were collected on identical quartz-type fiber filters (ADVANTEC, QR-100) with a diameter of 80 mm placed on the plate of each stage of the sampler. The length of the sampling tube was long enough so that the temperature was reduced to 50°C and condensation in the sampler was prevented by insulating the sampler.

PAHs Extraction Method

In this study, 16 PAH compounds are monitored. They include Naphthalene (Nap), Acenaphthylene (Act), Acenaphthene (Ace), Phenanthrene (Phe), Anthracene (Ant), Fluorene (Fle), Fluoranthene (Flu), Pyrene (Pyr), Benzo[a]anthracene (BaA), Chrysene (Chr), Benzo[a]pyrene (BaP), Benzo[b]fluoranthene (BbF), Benzo[k]fluoranthene (BkF), Dibenz[a,h]anthracene (DBA), Indeno[1,2,3-cd]pyrene (IDP), and Benzo[g,h,i]perylene (BghiPe). These PAH compounds are listed by the United States Environmental Protection Agency (USEPA) as priority pollutants (Leo, 2006). PAHs on sampled filters were extracted using an ultrasonic extraction (USE) technique. This method was modified from that used by Tang *et al.* (2005) and Furuuchi *et al.* (2006). A piece of each filter sample containing 4-5 mg of particulates was cut into small pieces (about 5 × 5 mm) and placed in a 125 mL flask. The filters were twice extracted ultrasonically with 40 mL of ethanol:benzene (1:3 v/v), for 15 min each. The recovery percentages of the 16 PAHs extracted are shown in Table 1. Then the solution was filtered by using 0.45 μm PTFE syringe filter and then 50 μL of dimethyl sulfoxide (DMSO) was added to the filtrate. The solution was concentrated using a Buchi rotary evaporator to remove ethanol and benzene, then re-dissolved with 450 μL of acetonitrile. Interfering compounds once again were removed with a 0.45 μm syringe filter. The filtrate was kept in a 1.5 mL amber glass vial, and stored in a refrigerator at -20°C prior to analysis.

High Performance Liquid Chromatography (HPLC) Analysis

The PAH extracts were analyzed using high-performance

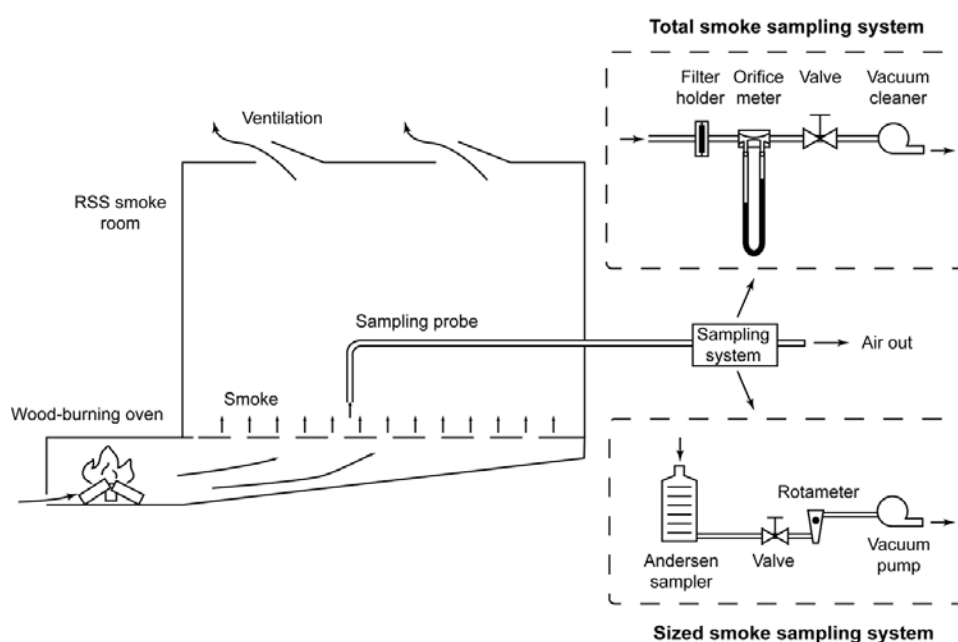


Fig. 1. Schematic diagram of smoke particle sampling methods.

Table 1. The recovery percentage of extraction for individual PAHs.

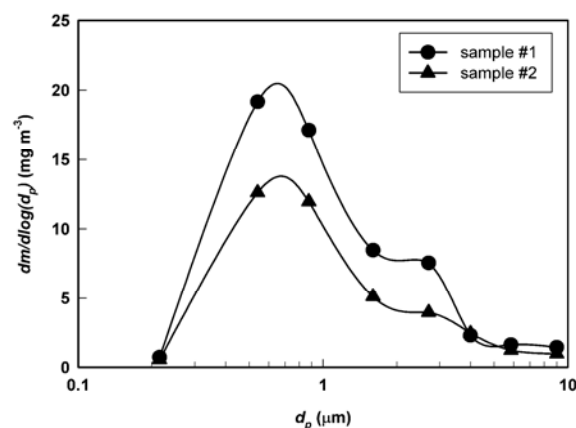
PAHs	Recovery (%)
Nap	47.50
Act	61.84
Ace+Fle	86.30
Phe	62.67
Ant	104.20
Flu	63.88
Pyr	126.24
BaA+Chr	71.44
BbF	73.78
BkF	74.75
BaP	100.62
DBA	74.55
BghiPe	72.55
IDP	81.50

liquid chromatography (Agilent, 1100) with ultraviolet absorption detection. HPLC/UV detection was performed following methods previously used for the detection of PAHs in environmental samples (Venkataraman *et al.*, 1999; Oanh *et al.*, 2000; Dionex, 2003) with appropriate modifications. A portion of the extract (25 μ L) was injected into a UPS C-18 reversed phase column (5 μ m, 4.6-mm diameter, 250-mm length) with guard column. The gradient elution of water/acetonitrile mobile phase was applied for compound separation at a flow rate of 1.0-1.2 mL/min. The PAHs were detected using a UV detector at 254-nm wavelength. The HPLC system was calibrated using external standards. The standard solutions were prepared from the 16 PAHs mix standards (Supelco, catalog number 4-8743). The resulting chromatograms present the different PAHs, which were then identified by matching the retention times and UV absorbance spectra with reference standards using the Chemstation program. The concentration of each compound was quantified from the peak area. A good linear correlation between the concentration and peak areas was found with R^2 values of 0.99 for every compound. Some sample extracts were spiked with the standard solutions to verify the location of each compound peak in the sample chromatograms. The limit of detection (LOD) was defined as the lowest concentration that the detector could provide a signal to noise ratio (S/N) greater than 3. The LOD in this study was determined to be well below 0.1 ng for the analyzed PAHs except Act (0.22 ng). The recovery percentage in this study was found to be in the range of 60-104% for each compound except Nap (47.5%).

RESULTS AND DISCUSSION

Size Distribution of Smoke Particles

Fig. 2 shows the results of size distribution measurements using an 8-stage Andersen sampler based on two samples of smoke particles collected from the combustion of rubber-wood in smoke rooms. The size distributions of the smoke particles indicates a single-mode behavior. They contained major particles in an accumulation mode, similar to the results of earlier investigations by Kalasee and Tekasakul (2003), Tekasakul *et al.* (2006) and Venkataraman *et al.* (2002). The mass median aerodynamic diameter (MMAD) is found to be 0.68 μ m and the geometric standard deviation (GSD) is 3.04 μ m. This is different from the results reported by Kalasee and Tekasakul (2003) as the experiments here were improved to prevent condensation in the sampler. The results show that the combustion of rubber-wood emits a large fraction of fine particles.

**Fig. 2.** Size distribution of smoke particles from rubber-wood burning.

Concentration of Smoke Particles

The effects of moisture content and wood burning period on particle concentration from three samples in which the moisture contents vary from 37.4% (rather dry condition) to 73.6% (wet condition) are shown in Fig. 3. The presence of water in the rubber-wood results in incomplete combustion, hence, a thick cloud of smoke particles. Therefore, an increase of moisture content would result in an increase of smoke particle concentration. The concentration of smoke particles decreases during the course of combustion. This is because the water in the wood eventually evaporates and the degree of incomplete combustion is reduced.

The highest concentrations were found to be 23.35 to 47.54 mg/m^3 upon initial combustion for the wood moisture contents of 37.4 to 73.6% d.b. (dry basis) as shown in Fig. 3. After 120 minutes, they were reduced to 4.57 to 3.65 mg/m^3 . During normal operation, fuel wood is re-supplied to the oven every 120 minutes, though the experiment here was conducted for 135 minutes. If the average value of smoke concentration during this period (15.81 mg/m^3) is used in calculations, the total mass of smoke particles emitted to the workplace and atmospheric environment is as high as 4.33 kg/month/room assuming an average velocity of the smoke particle aerosol through two ventilating lids (60 cm \times 60 cm each) of 2.62 m/sec (Promtong and Tekasakul, 2007).

Concentration of PAHs

Effect of Moisture Content and Wood Burning Period on PAH Concentration

Data of the concentration of each PAH compound for different wood moisture contents and burning periods are shown in Table 2. These data are presented graphically in Figs. 3-6. The PAH concentration normalized to the cancer potency equivalent factor of Benzo[a]pyrene or the BaP Toxic Equivalence (BaP-TEQ) is also given in the table. It can be calculated from (Orecchio and Papuzza, 2009)

$$\text{BaP-TEQ} = \sum_i (\text{PAH}_i \times \text{TEF}_i) \quad (1)$$

where PAH_i is the concentration of PAH congener i ; and TEF_i is the toxic equivalent factor for PAH congener i obtained from Collins *et al.* (1998).

The effects of moisture content and burning period on the total concentration of the sixteen PAH compounds is illustrated in Fig. 3. In this work, the PAH compounds will be classified in two groups; 2-3 rings and 4-6 rings. The 2-3 ring PAH mass fraction consists of NaP, Act, Ace+Fle, Phe, and Ant, while the 4-6 ring

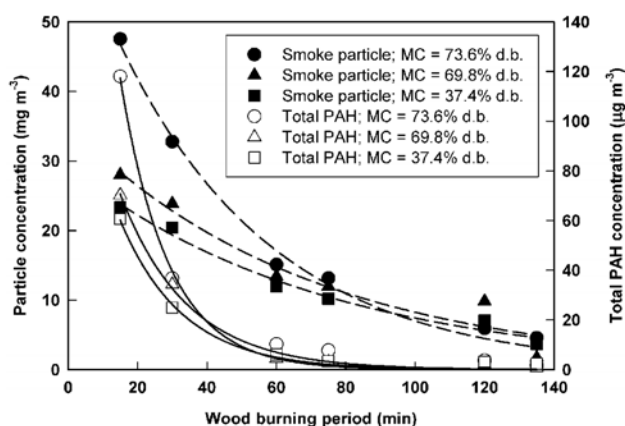


Fig. 3. Effect of wood burning period on the total PAH concentration and smoke particle concentration for different wood moisture contents.

PAHs include Flu, Pyr, BaA+Chr, BbF, BkF, BaP, DBA, BghiPe, and IDP. The variation of the PAH concentration with respect to burning period and moisture content is similar to the relationship exhibited by the smoke particle concentration. The highest concentrations of 60.59 to 118.06 $\mu\text{g}/\text{m}^3$ were observed in the initial burning periods for wood moisture contents of 37.4 to 73.6% d.b. (Fig. 3). These are equivalent to BaP-TEQ of 11.69 to 23.97 $\mu\text{g}/\text{m}^3$, respectively. After 120 minutes, they were reduced to 3.20 (0.94 BaP-TEQ) and 3.76 (0.43 BaP-TEQ) $\mu\text{g}/\text{m}^3$ for moisture contents of 37.4% and 73.6% d.b., respectively. The relationship between total PAH concentration and smoke particle concentration exhibits a power function form (Fig. 4). Low concentrations of PAHs after a long period of combustion may result, in part, from the decomposition of the PAHs.

Relationship between the concentration of 4-6 ring PAHs, which are particle-bound, and wood burning period is shown in Fig. 5. It shows that the PAH concentration is reduced exponentially during the course of combustion. The influence of burning period and fuel moisture content on the concentration of 4-6 ring PAHs is similar to the influence on total PAH concentration and smoke particle concentration. The relationship between smoke particle concentration and 4-6 ring PAH concentration is shown in Fig. 6. The results indicate that 4-6 ring PAH concentration and total PAH concentration exhibit a non-linear dependence on smoke particle concentration. Total PAH, 4-6 ring PAH and smoke particle concentrations are highest in the initial combustion period followed by a dramatic decrease during the course of combustion. Most of the decrease in PAH concentration occurs during first hour of the combustion process. This is probably the result of decomposition and evaporation of PAHs. The combustion temperature peaked 1 hour after rubberwood was fed, and then it was reduced (Promtong and Tekasakul, 2007).

Profile of PAHs

Data of the mass fraction for each PAH compound for different wood moisture contents and burning periods are shown in Table 3. These data are presented graphically in Figs. 7-10. The congener profile of 16 PAHs in smoke particles generated from rubber-wood combustion in a smoke room is obtained by averaging data from 18 samples and is shown in Fig. 7. It shows that the dominant PAH components include 2-3 ring PAHs and 4-6 ring PAHs; in particular, BghiPe, on average, accounts for approximately 16.8% of the total PAHs. In the case of white-wood combustion, BaP has been shown to be the dominant PAH component (Hay et al. 2003). Moreover, the relative concentration of 4-6 ring PAHs in the atmospheric environment

Table 2. Concentration of each PAH compound measured at three wood moisture contents (MC) for six different burning periods. Unit is in ng/m^3 .

PAHs	MC = 73.6% d.b.						MC = 69.8% d.b.						MC = 37.4% d.b.										
	15		30		60		15		30		60		15		30		60		120		135		
	Burning Period (min)	Concentration	Burning Period (min)	Concentration	Burning Period (min)	Concentration	Burning Period (min)	Concentration	Burning Period (min)	Concentration	Burning Period (min)	Concentration	Burning Period (min)	Concentration	Burning Period (min)	Concentration	Burning Period (min)	Concentration	Burning Period (min)	Concentration	Burning Period (min)	Concentration	
Nap	4645.79	3321.19	935.90	782.88	325.98	184.48	3059.02	2608.84	420.46	331.23	179.80	78.53	1206.19	765.99	235.63	123.31	126.77	78.06					
Act	7522.43	3546.13	1581.65	1427.01	445.86	197.45	5521.86	2937.50	629.93	545.10	284.02	112.31	1838.76	2417.10	511.26	285.55	198.62	192.48					
Acet+Flu	20834.71	6931.36	1055.64	830.04	554.48	399.70	12786.19	6868.03	441.16	309.34	335.89	187.62	12182.74	3735.34	919.97	514.08	614.83	487.08					
Phe	667.75	7.77	2.14	4.70	30.02	0.65	389.68	213.77	1.94	1.91	0.55	0.49	325.73	44.25	25.99	1.66	2.52	10.64					
Ant	459.68	93.55	173.62	62.17	82.98	56.82	245.43	309.83	39.26	29.61	34.54	25.02	79.25	24.91	6.81	5.08	4.00	3.20					
Flu	1352.00	221.99	298.02	206.08	188.86	0.59	837.83	332.54	125.14	84.64	58.88	1.66	1716.87	98.32	3.80	4.00	3.06	1.95					
Pyr	7153.02	2743.96	1061.60	847.57	355.70	19.47	4243.07	2836.53	516.30	337.59	209.33	13.43	49.10	371.55	101.28	41.09	43.72	27.25					
BaA+Chr	17035.13	2897.05	466.66	450.94	292.82	150.64	9700.13	2991.75	238.76	192.33	156.22	61.02	9802.35	1429.68	336.11	189.63	130.36	115.04					
BbF	9395.53	3329.31	716.99	533.64	302.68	134.59	5466.11	3426.28	346.73	244.97	164.53	61.33	6919.82	2763.83	595.12	315.91	270.26	167.63					
BkF	9228.21	2849.78	525.47	400.41	199.69	75.94	5289.16	2607.10	103.82	162.91	103.82	38.28	6252.51	2698.62	561.41	284.99	238.03	120.10					
BaP	10754.42	3057.24	589.45	388.59	162.56	78.43	5811.10	2471.24	242.93	154.64	98.27	34.90	6127.95	2205.55	457.56	253.91	175.37	152.76					
DBA	9961.36	1460.04	379.42	389.21	187.86	141.66	6378.40	1134.08	227.25	104.04	95.23	31.49	3464.08	1515.79	530.16	431.22	682.40	529.47					
BghiPe	15649.58	5227.01	2021.06	1163.58	534.08	230.14	8852.94	4631.95	855.72	489.36	331.48	124.75	8803.80	5760.70	1516.87	809.38	543.53	411.36					
IDP	3202.20	1046.18	446.57	292.54	97.52	26.89	1683.48	916.28	120.25	84.65	54.59	16.28	1799.79	1174.45	308.63	163.76	161.54	98.93					
Total	118061.81	36732.55	10254.19	7779.36	3761.11	1697.44	70264.41	34285.73	4428.63	3072.34	2107.14	787.12	60588.95	25006.08	6110.60	3423.58	3195.00	2395.95					
4-6 ring	83931.46	22832.56	6505.24	4672.56	2321.78	858.34	48262.22	21347.76	2895.87	1855.15	1272.34	383.15	44936.28	18018.49	4410.94	2493.89	2248.25	1624.49					
2-3 ring	34130.36	13899.99	3748.95	3106.79	1439.33	839.09	22002.19	12937.98	1532.76	1217.19	834.80	403.97	15652.67	6987.60	1699.66	929.69	946.75	771.46					
BaP-TEQ	23973.40	5454.64	1187.99	939.36	433.12	255.04	14036.20	4515.09	562.18	324.35	238.33	82.92	11685.53	4521.80	1168.08	780.19	937.74	731.59					

of Hat Yai city (Tekasakul *et al.* 2008), which is surrounded by several RSS cooperatives, is lower than those obtained in this work. This seems to demonstrate the decomposition of PAHs, from rubber-wood combustion, by sunlight during atmospheric transport.

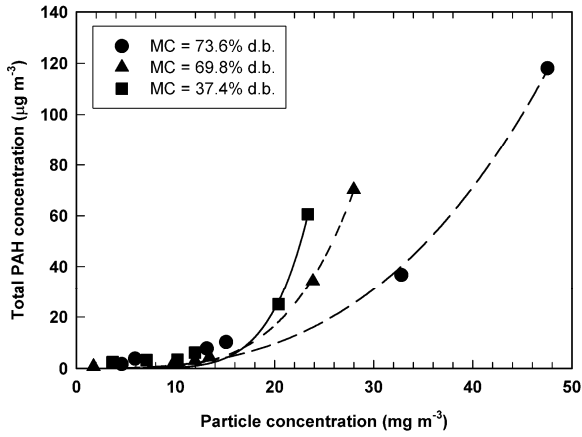


Fig. 4. Relationship between total PAH concentration and smoke particle concentration for different wood moisture contents.

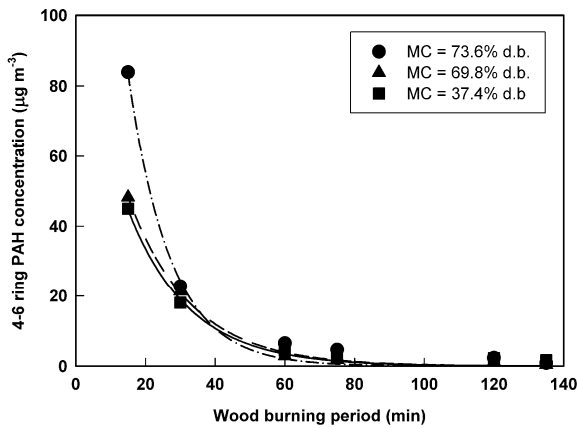


Fig. 5. Relationship between the concentration of 4-6 ring PAH compounds and wood-burning period for different wood moisture contents.

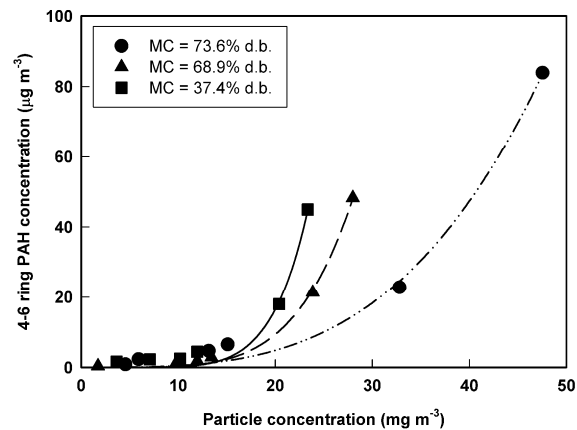


Fig. 6. Relationship between the concentration of 4-6 ring PAH compounds and smoke concentration for difference wood moisture contents.

Table 3. Relative mass concentration for each PAH compound for different wood burning period and wood moisture contents (MC). Unit is in %.

PAHs	MC = 73.6% d.b.												MC = 69.8% d.b.												MC = 37.4% d.b.											
	15				30				60				75				15				30				60				75							
	Burning_Period (min)	15	30	60	75	Burning_Period (min)	15	30	60	75	Burning_Period (min)	15	30	60	75	Burning_Period (min)	15	30	60	75	Burning_Period (min)	15	30	60	75											
Nap	3.94	9.04	9.13	10.06	8.67	10.87	4.35	7.61	9.49	10.78	8.53	9.98	3.06	3.86	3.60	3.97	3.26	3.97	3.86	3.60	3.97	3.26	3.97	3.86	3.60	3.97	3.26									
Act	6.37	9.65	15.42	18.34	11.85	11.63	7.86	8.57	14.22	17.74	13.48	14.27	9.67	8.37	8.34	6.22	8.03	9.67	8.37	8.34	6.22	8.03	9.67	8.37	8.34	6.22	8.03									
Acet+Flu	17.65	18.87	10.29	10.67	14.74	23.55	18.20	20.03	9.96	10.07	15.94	23.84	20.11	14.94	15.06	19.24	20.33	20.11	14.94	15.06	19.24	20.33	20.11	14.94	15.06	19.24	20.33									
Phe	0.57	0.02	0.02	0.06	0.80	0.04	0.55	0.62	0.04	0.06	0.03	0.06	0.54	0.18	0.43	0.05	0.44	0.54	0.18	0.43	0.05	0.44	0.54	0.18	0.43	0.05	0.44									
Ant	0.39	0.25	1.69	0.80	2.21	3.35	0.35	0.90	0.89	0.96	1.64	3.18	0.13	0.10	0.11	0.15	0.13	0.13	0.10	0.11	0.15	0.13	0.13	0.10	0.11	0.15	0.13									
Flu	1.15	0.60	2.91	2.65	5.02	0.03	1.19	0.97	2.83	2.75	2.79	0.21	2.83	0.39	0.06	0.12	0.08	2.83	0.39	0.06	0.12	0.08	2.83	0.39	0.06	0.12	0.08									
Pyr	6.06	7.47	10.35	10.90	9.46	1.15	6.04	8.27	11.66	10.99	9.93	1.71	0.08	1.49	1.66	1.20	1.37	1.71	1.49	1.66	1.20	1.37	1.71	1.49	1.66	1.20	1.37									
BaA+Chr	14.43	7.89	4.55	5.80	7.79	8.87	13.81	8.73	5.39	6.26	7.41	7.75	16.18	5.72	5.50	4.08	4.80	16.18	5.72	5.50	4.08	4.80	16.18	5.72	5.50	4.08	4.80									
BbF	8.13	9.06	6.99	6.86	8.05	7.93	7.78	9.99	7.83	7.97	7.81	7.79	11.42	11.05	9.74	8.46	7.00	11.42	11.05	9.74	8.46	7.00	11.42	11.05	9.74	8.46	7.00									
BkF	7.82	7.76	5.12	5.15	5.31	4.47	7.53	7.60	5.03	5.30	4.93	4.86	10.32	10.79	9.19	8.32	7.45	10.32	10.79	9.19	8.32	7.45	10.32	10.79	9.19	8.32	7.45									
BaP	9.11	8.32	5.75	5.00	4.32	4.62	8.27	7.21	5.49	5.03	4.66	4.43	10.11	8.82	7.49	7.42	5.49	10.11	8.82	7.49	7.42	5.49	10.11	8.82	7.49	7.42	5.49									
DBA	8.44	3.97	3.70	5.00	4.99	8.35	9.08	3.31	5.13	3.39	4.52	4.00	5.72	6.06	8.68	12.60	21.36	5.72	6.06	8.68	12.60	21.36	5.72	6.06	8.68	12.60	21.36									
BghiPe	13.26	14.23	19.71	14.96	14.20	13.56	12.60	13.51	19.32	15.93	15.73	15.85	23.04	24.82	23.64	17.01	17.17	23.04	24.82	23.64	17.01	17.17	23.04	24.82	23.64	17.01	17.17									
IdP	2.71	2.85	4.36	3.76	2.59	1.58	2.40	2.67	2.72	2.76	2.59	2.07	2.97	4.70	5.05	4.78	5.06	2.97	4.70	5.05	4.78	5.06	2.97	4.70	5.05	4.78	5.06									

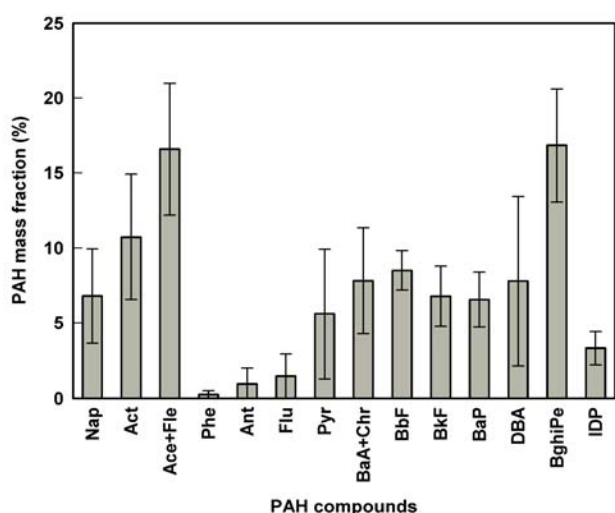


Fig. 7. Mass fraction of each PAH compound in smoke particle samples from rubber-wood burning (n = 18).

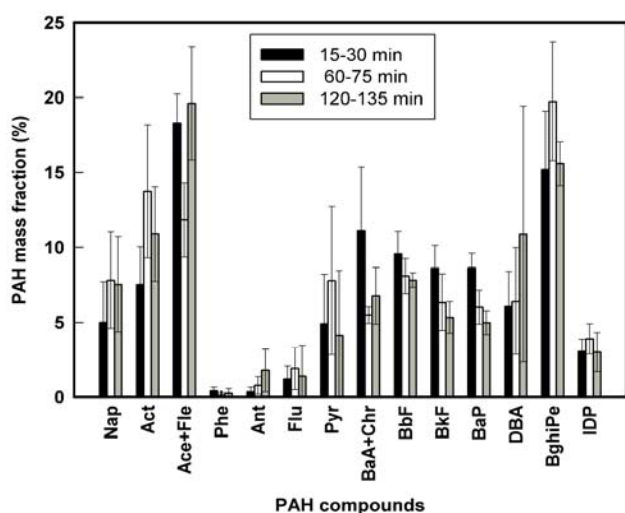


Fig. 8. Distribution of PAH compounds for all investigated conditions calculated as a percentage for each compound in relation to the total amount of PAH compounds for different burning periods.

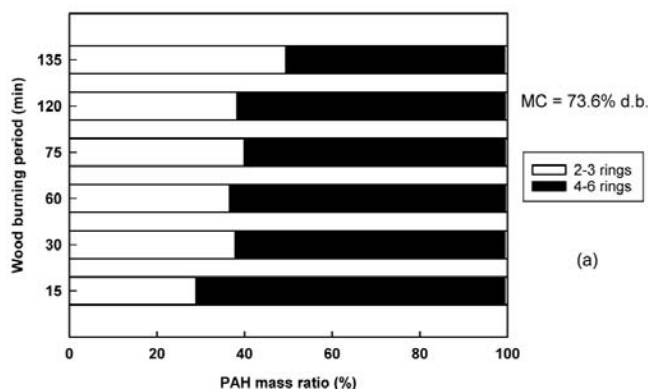


Fig. 9. Mass ratios of 2-3 ring PAH compounds to 4-6 ring PAH compounds for each wood-burning period for different wood moisture contents: (a) MC = 73.6% d.b., (b) MC = 69.8% d.b., (c) MC = 37.4% d.b.

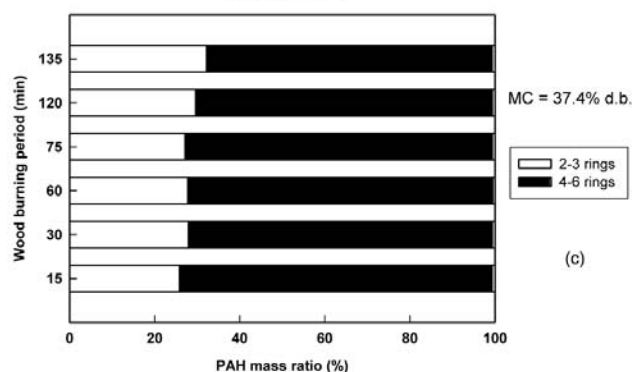
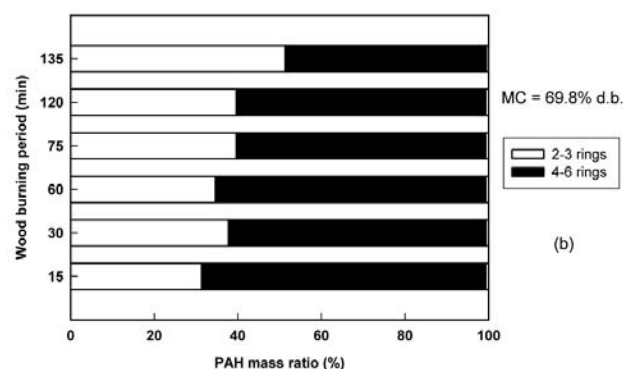


Fig. 9. (continued).

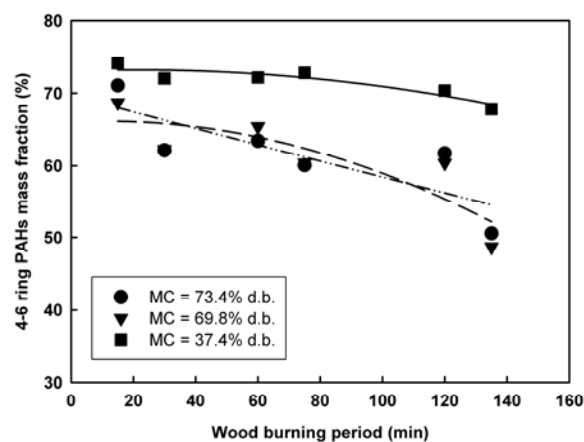


Fig. 10. Relationship between mass fraction of 4-6 ring PAH compounds and wood burning period for different wood moisture contents.

Effect of Wood Burning Period and Wood Moisture Content on PAH Contribution

The contribution of PAH compounds for different wood-burning periods is shown in Fig. 8. It was found that the mass fraction contribution of each PAH compound is not significantly different for different burning periods. However, the PAH mass fraction is dominated by BghiPe, Ace+Fle, Act, and NaP. They contribute to more than 45% of the total PAH emissions for all wood-burning periods. This is different from the results of birch-wood combustion (Hedberg *et al.*, 2002). For birch-wood, the major PAH emissions include Fle, Phe, Ace, Flu and Pyr, contributing to more than 70% of the total PAH emissions. Figs. 9(a)-(c) show the mass ratios of 2-3 ring PAHs to 4-6 ring PAHs for different burning period and moisture contents. High

molecular weight PAHs (4-6 rings) contribute to more than 60% of the total PAH emissions for all values of wood moisture contents. They show that during the first hour of combustion, the fraction of 2-3 ring PAH compounds in the particulate phase is low. It slightly increases as the combustion progresses. Fig. 10 shows the relationship between the mass fractions of 4-6 ring PAH compounds and the wood-burning period. The mass fraction of 4-6 ring PAH compounds decreases slightly in an opposite manner of their 2-3 ring counterparts. The smaller fraction of 2-3 ring PAH compounds during the first hour of combustion results from the higher rates of evaporation and decomposition compared to those of 4-6 ring PAH compounds. This is due to the high combustion temperature. Approximately one hour into the wood burning cycle, the combustion temperature decreases (Promtong and Tekasakul, 2007) so that the rate of evaporation and decomposition of 2-3 ring PAH compounds subsides, and 2-3 ring PAH compounds represent a larger mass fraction.

CONCLUSIONS

The smoke particles from the rubber-wood burning exhibit a single-mode size distribution consisting of a major part of fine particles smaller than 2 μm in which the mass median aerodynamic diameter (MMAD) is 0.68 μm . The total smoke concentration depends on the wood moisture content and wood burning period. An increase of the wood moisture content exponentially enhances the smoke concentration. The smoke particles were reduced as the combustion time progresses. The PAH concentration shows a similar dependence on wood moisture content and wood burning period. In addition, the PAH concentration exhibits a non-linear dependence on smoke particle concentration, underscoring the significance of wood moisture content and burning period with respect to both physical and chemical characteristics of smoke particles. This work should aid in the improvement of air quality for workers and other inhabitants that share a common atmospheric environment with RSS cooperatives.

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