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# Workplace Environment and Personal Exposure of PM and PAHs to Workers in Natural Rubber Sheet Factories Contaminated by Wood Burning Smoke

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## ABSTRACT

The workplace environment in factories producing ribbed smoked sheet rubber (RSS), the interiors which are heavily contaminated by wood burning smoke, was evaluated with a focus on the concentration of suspended particulates and particle-bound PAHs as well as workers' exposure in the breathing zone during the period January, 2006–February, 2008 in Thailand. Seasonal changes in particulate and PAH concentrations are discussed in relation to the amount of RSS produced, wind direction, ventilation type and the geometry of the factory building. The concentration of particulate matter in the workplace was shown to increase nearly linearly with RSS production while being influenced by the wind direction to the open sides of the building and wind speed. Particulate concentrations in the workplace and in the worker's breathing zone were lower than those for other common occupational exposure limits. However, rather high PAH concentrations of 97.4 ± 129 ng/m$^3$ and 142 ± 184 ng/m$^3$ were found in the workplace and in the breathing zone, respectively. BaP$_{TEQ}$ concentrations in the workplace ranging from 21.4 to 91.0 ng/m$^3$ were similar to those in a sinter plant. The workers' exposure to PAHs was similar to that in a sinter plant, a metal recycling plant, a paving bitumen manufacturing plant and a carbon black manufacturing plant. The mass fraction of PAHs in particles in the RSS factory was as high as 0.30 BaP$_{TEQ}$ ng/μg, much higher than that in a carbon black plant (0.004–0.01 BaP$_{TEQ}$ ng/μg). The results reported herein suggest that the workers in the RSS factory have a somewhat high health risk from exposure to PAHs. Natural ventilation by the addition of roof turbines was insufficient in terms of reducing PAHs levels in the workplace although a roof ridge vent was functional and had a positive effect.

***Keywords:*** Smoke; Polycyclic aromatic hydrocarbon; Ribbed smoked sheet; Exposure; Fine particles.

## INTRODUCTION

Thailand is the world leader in the production and export of natural rubber (*Hevea brasiliensis*), and produced 2.9 million metric ton in 2007 (Thailand Rubber Research Institute, 2007). The white liquid obtained from rubber trees, called "rubber latex", is used as raw material in the production of five intermediate products of the rubber before they are used in downstream rubber industries that produce rubber tires, medical gloves, condoms, rubber bands, flexible tubing, etc. These intermediate products include the production of ribbed smoked sheets (RSS), air dried sheets (ADS), block rubber, crepe rubber, and concentrated rubber. RSS constitutes a major portion, accounting for 43% of the total product, while block rubber and concentrated latex account for 36% and 17%, respectively.

The production of RSS has shifted from large-scale industries to community-level factories called "Cooperatives", which are located near rubber tree plantations, each of which produces about 500–1,000 metric tons of RSS per year. Most RSS cooperatives, currently a total of 444, are located in the southern Thailand, in the provinces of Nakon Si Thamarat, Surat Thani, Trang, Songkhla and other southern provinces (Furuuchi *et al.*, 2006; Office of the Rubber Replanting Aid Fund, 2008).

During the production of the RSS, fuel-wood (usually old rubber-wood) is burned in a burner to supply heat to the wet rubber sheets in the smoke (drying) rooms in order

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to remove moisture. According to the authors' survey, RSS production is about 40–50 tons per cooperative during the peak season of November-January while for each ton of RSS, about 0.8–1.2 ton of fuel-wood is consumed (Promtong and Tekasakul, 2007): about 60 tons of fuel-wood is consumed for each cooperative during the peak months of operation. Although self-driven roof ventilating turbines or roof ridges are used in some cooperatives, not all have pollution control devices and, as a result, the smoke is released into the factory workplace area through ventilating lids on the roof of the smoke room which open directly to the inside of the factory building. Hence, in many cases, the workplace is heavily contaminated by smoke, which has previously been shown to contain high levels of certain hazardous species, e.g., polycyclic aromatic hydrocarbons (PAHs), or, typical carcinogenic agents (WHO, 2002; Chomanee *et al.*, 2009). According to a previous investigation (Choosong *et al.*, 2007), the concentration of PAHs at the breathing zone of workers in an RSS cooperative was in the range of that for asphalt workers (0.03–426 ng/m$^3$: gas and particulates), and much less than that in an aluminum reduction plant (0.57–1.7 µg/m$^3$) and an electrode paste plant (2.0–10.6 µg/m$^3$). Workers are required to be in the smoke room periodically and some workers who live in the factory are exposed to smoke nearly 24 hours per day, throughout the year without the availability of any mask or filter. Such situations likely have a serious influence on workers' health. However, detailed information on the working environment throughout a year is lacking. Information concerning the amount of RSS produced during such a period of time, meteorological conditions such as wind direction and the geometry of the factory building, as related to the ventilation method, would be useful to have, in terms of evaluating the overall situation.

In the present study, the working environment in some selected rubber cooperatives in Songkhla and Phatthalung provinces, Thailand were monitored throughout 2006 to 2008. The focus of the study was on the collection of data concerning the concentration of total and size fractionated smoke particles as well as particle-bound PAHs in relation to the amount of RSS produced, wind direction and ventilation equipment used. The job characteristics of workers exposed to particulates and particle-bound PAHs are also discussed in relation to the workplace environment.

### *Geometry of RSS Factory Buildings*

The geometry of RSS factory buildings can be classified into two models, based on the date of their establishment, i.e., the so called an "old model" established before 1995 and the "new model" after 1995. Each type has a different number of RSS smoke rooms. The old model contains seven smoke rooms (W × H × L = 2.6 × 3.7 × 6.2 m) while the new model contains four rooms of double size (W × H × L = 5.2 × 3.7 × 6.2 m). The capacity of an old-model smoke room is about 1,250 kg on a dried RSS basis while that for the new model is double. Fuel-wood consumption is typically about 800–1,200 kg per ton of dried RSS.

The layout of the main RSS factory studied in this work, the Saikao cooperative, located in the Muang district, Songkhla province is shown in Fig. 1. It is a new model and is referred to as "Coop-1" in the following discussion. The roof of each smoke room opens to the workplace of the factory via two ventilating lids. Heat and smoke to the smoke room is supplied from the bottom through a flue passage from a burner located outside the building, where rubber-wood is burned as fuel. The temperature in the burner was not measured but is estimated to be around 300-500°C, similar to residential wood burning (McDonald *et al.*, 2000). There are no air outlets on the roof of the factory, which was originally designed with little attention being paid to the working environment. However, the side of the building opposite to the smoke room is open to the outside, ambient environment (designated by double-arrow lines). Part of the smoke from the smoke room first rises toward the roof and then flows down to the floor before leaving the factory. The remaining part of the smoke vents out of the factory via openings on the rear side. Because the geometry is opened to the ambient atmosphere, ventilation by outside air is an important aspect of the situation, but it could be affected by wind direction and speed as well as ambient particulate concentration.

Although most of the factory buildings can be classified into the above two models, some cooperatives have recently used additional facilities for air ventilation. Fig. 2 shows the geometries of factories with different types of additional ventilation facilities, roof ventilating turbines (Coop-2 and 3) and roof ridge vents (Coop-4), studied in this work. The construction of these ventilation facilities constituted attempts to improve ventilation, their performances have not been evaluated quantitatively, although have the impression that this improves working conditions. Coop-4 has a different geometry. Three larger smoke rooms were added and a roof ridge vent was installed in the previous section. The dimensions and characteristics of the four cooperatives studied in this work are summarized in Table 1.

### *RSS Production Process and JOB Characteristics of Workers*

In the RSS production process, fresh rubber latex, tapped from rubber trees, is transported to the RSS factory from rubber plantations by farmers who are members of the cooperative. This is done during 7 A.M.–11 A.M. After the latex is obtained, e.g., after 8:30 A.M. until noon, it is poured to pools located on the lower floor where it becomes a solid (see Fig. 1). After mixing the latex with water and formic acid, aluminum spacers are immersed in the latex and used as partitions to produce sliced slabs (around 3 cm × 50 cm × 50 cm) of solidified latex, which requires approximately three hours. After being solidified at around 2 P.M., the latex slabs are washed in a long water rail which carries the slabs to a squeezing machine where they are squeezed to form ribbed sheets (3 to 4-mm thick). They are then hung on a cart that contains racks before they are dried in a smoke room. The hanging process requires 15–20 minutes per cart. The amount of RSS produced depends on the amount of the latex used,

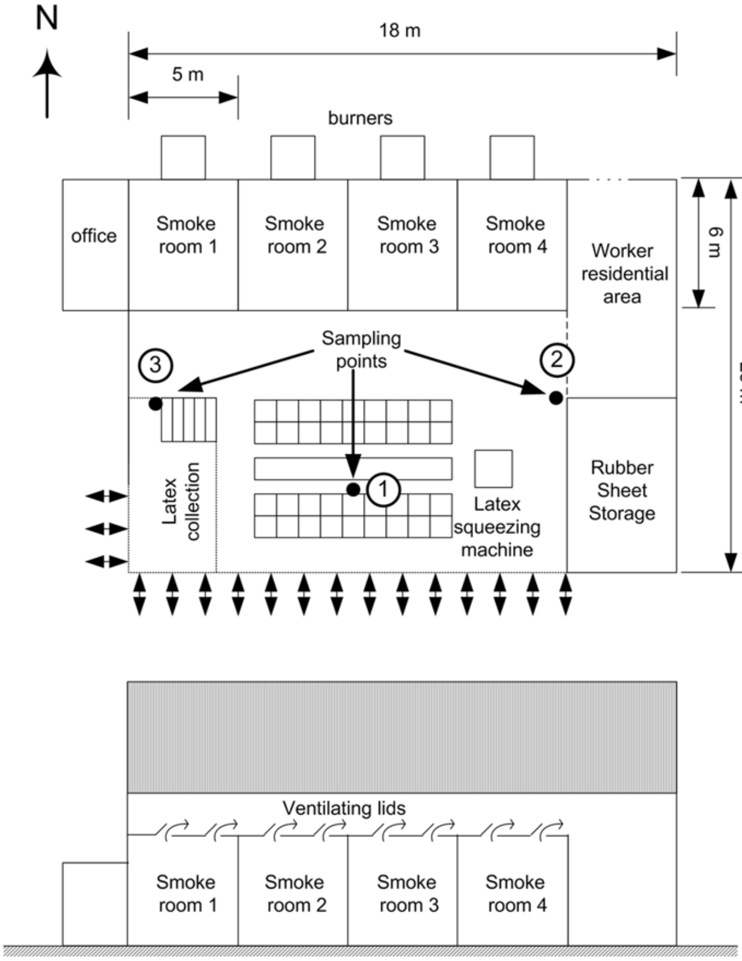

**Fig. 1.** Layout of the Saikao cooperative (Coop-1) located in the Muang district, Songkhla province.

with more than 2,000 sheets per day being produced during the high season (e.g., January to February), and 1,000–1,500 sheets per day during the moderate season (e.g., May to July). In general, all processes end before 5 P.M. although it is sometimes delayed up to 8 P.M. depending on the latex supply. Pressed sheets are left overnight, to permit a portion of the moisture to evaporate and are then dried in a smoke room. The evaporation period typically requires about 12–15 hours. The drying of rubber sheets in a smoke room generally is completed in 3–4 days for a batch, when the temperature is 40ºC in the first day and around 60ºC in subsequent days. Many workers also help to push the rubber-hanging cart into the smoke rooms and they stay in the smoke room for about 10 minutes per day. During the smoking process, workers must enter the smoke rooms to periodically check the quality of the rubber sheets, with an exposure time of at least 5 minute per room. Workers also feed rubber wood as fuel into the burners 5–6 times a day. These are the periods when they are directly exposed to highly concentrated smoke particles from the wood burning. Although workers do not exactly follow the procedure and the working period changes with the amount of collected latex, it is mostly followed during the routine production of RSS.

Workers are also exposed to smoke as it exits from the smoke rooms and is slightly diluted inside the factory building, for almost an entire day, even though they spend some time outside the factory for breaks during work. Most of the workers reside in a floor space inside the factory adjacent to the workplace area (Fig. 1) so that they are continuously exposed to some smoke throughout the year. This is a typical problem for RSS cooperatives.

## METHODOLOGY

In this section, methodologies for air sampling, chemical analysis of particulates, and the acquisition of meteorological data and the quantity of RSS produced are described.

### *Air Sampling*

The sampling of airborne particulates was conducted for two different purposes: to obtain information on the characteristics of the workplace aerosol, and to evaluate the personal exposure of workers to aerosol particulates in the breathing zone. In the Saikao cooperative factory (Coop-1), which employs the "new-type" geometry, both the characteristics of, and personal exposure to workplace aerosol and PAHs were evaluated throughout the period of one year. In other factories with different geometries and

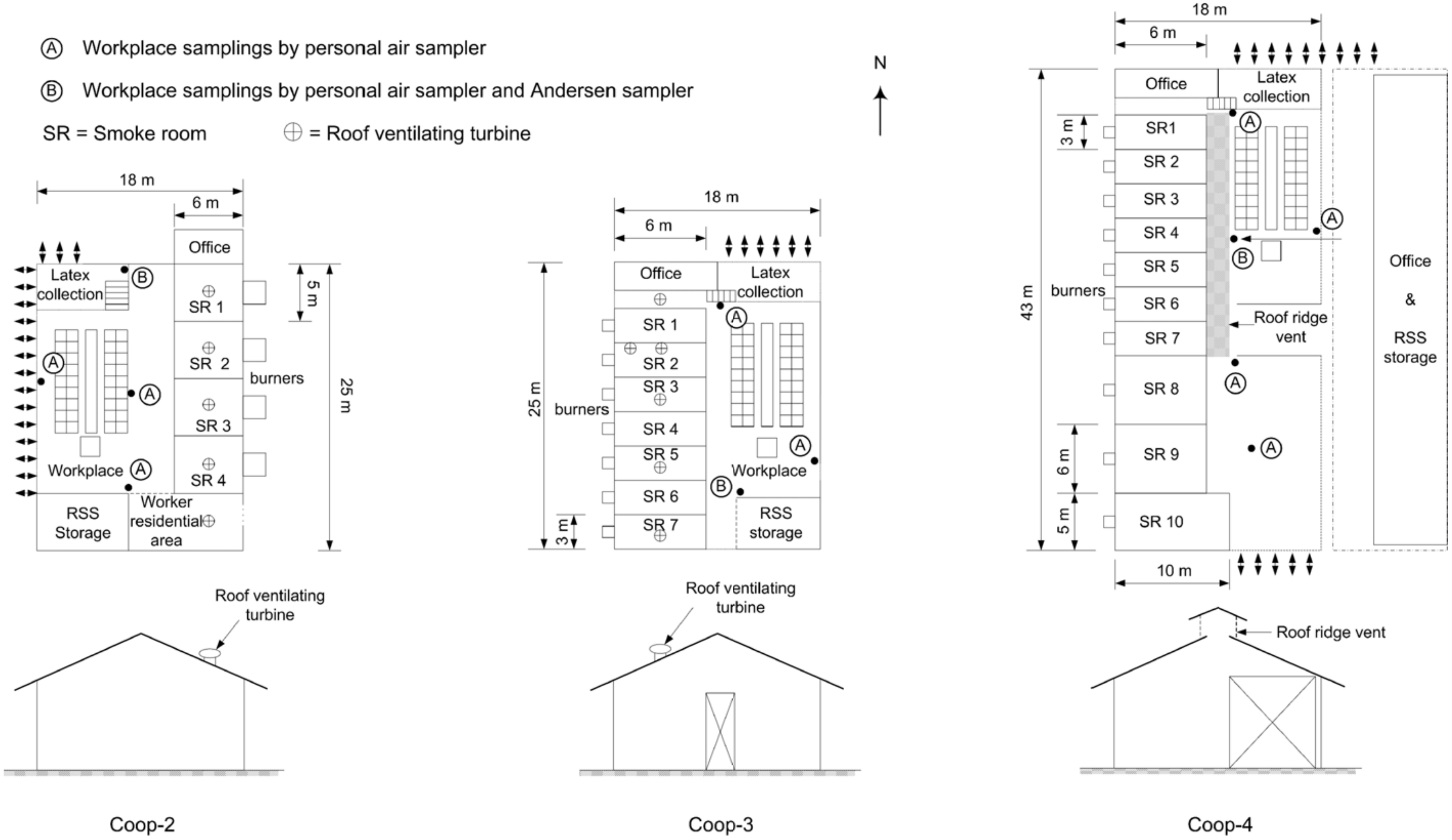

**Fig. 2.** Geometries of factories with different types of additional ventilation facilities (Coop-2 to Coop-4).

**Table 1.** Information on RSS factories investigated in this study.

| | Coop-1 | Coop-2 | Coop-3 | Coop-4 |
|---|---|---|---|---|
| Location (district, province) | Muang, Songkhla | Bangklam, Songkhla | Sadao, Songkhla | Khaochaison, Phatthalung |
| Model | new | new | Old | Old + new |
| Number of workers | 6 | 7 | 4 | 8 |
| Worker's residue place | inside factory | inside factory | outside factory | outside factory |
| Ventilation | opened sides | opened sides + roof turbines | opened sides + roof turbines | opened sides + roof ridges |
| Number of smoke rooms | 4 | 4 | 7 | 10 |
| Smoke room dimension | 5 × 6 m | 5 × 6 m | 3 × 8 m | 3 × 8 m |
| | | | | 6 × 8 m |
| | | | | 5 × 10 m |
| Squeezing machine | diesel | electric | electric | diesel |

ventilating facilities, workplace and personal sampling were conducted during some selected seasons during the study year. Results of these findings are discussed below.

Sampling in the workplace was conducted at three different positions in Coop-1 as shown in Fig. 1: two sampling positions on the ground floor section at a level of 1.5 m above the floor (Position-1 and Position-2) and one sampling position near the top of the steps between the ground floor and a side entrance which is elevated by approximately 2.5 m above the ground floor (Position-3). Samplings at Position-1 and Position-2 were conducted by personal air sampling pumps (Gilair-5, Sensidyne Inc, and SKC Universal PCXR8, SKC Inc, flow rate 2 L/min, NIOSH method 0500) equipped with total dust inlets and quartz fibrous filters (ADVANTEC, QR-100, 37 mm diameter) during the period August 2006 to February 2008. Sampling period was 24–40 hours. Sampling at Position-3 was achieved by a high volume air sampler (Shibata, HV500F, flow rate 500 L/min) for total suspended particulates (TSP) and an Andersen cascade impactor (Tokyo dylec, AN-200, 8-stages, flow rate 28.3 L/min) for size-fractionated particulate matter. The TSP sampling period was 12 hours and data were collected every two weeks during January to December 2006. The Andersen sampling period was 5 days to 2 weeks and was carried out during September 2006–February, 2008.

Same personal air sampling units were used for breathing-zone sampling for workers who worked in the factory. In contrast to the workers sampling where the positions are fixed, the positions of workers' breathing-zone sampling move with the worker. Total particle concentration was sampled during the daily working period (6–8 hours), where an inlet tube was attached to a worker's collar, and at least two workers participated simultaneously in the sampling. The breathing-zone sampling was conducted during August 2006 to July 2007 excluding April 2007 because no workers were on site in this month. The sampling periods and conditions are summarized in Table 2.

### *Analysis of Chemicals*

Filters were conditioned in a desiccator at room temperature ~25°C and a relative humidity ~50% for at least 48 hours before being weighed to obtain initial weights and were then used for the sampling. After the sampling, they were weighed after 48 hours of the same conditioning procedure. The resulting materials were then analyzed to determine the concentrations of particle-bound PAHs. Fifteen different PAH compounds–Naphthalene (Nap), Acenaphthene (Ace), Phenanthrene (Phe), Anthracene (Ant), Fluorene (Fle), Fluoranthene (Flu), Pyrene (Pyr), Benz[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[ghi] perylene (BghiPe)–were analyzed by HPLC (HITACHI/L-2130/2200/2300/2485) with a fluorescence detector and an Inertsil ODS-P column (5 µm, 3.0 mm diameter, 250 mm length) + acetonitrile/ultra-pure water mobile phase after ultrasonically dissolving the samples on the filter in an ethanol/benzene (1:3) solution, followed by evaporation on a rotary vacuum evaporator (Toriba *et al.*, 2003). The average recovery efficiency for 15 components was confirmed to be 0.82 ± 0.12 (n = 3) by adding a standard reagent [Accustandard 0.2 mg/mL in $CH_2Cl_2$: MeOH (1:1)] to the samples (Tang *et al.*, 2005). The values of PAHs from 3 travel blank filters were subtracted from the values determined by analysis: 8.5 ± 5 pg/cm$^2$ for 2–3 ring PAHs and 5.5 ± 5 pg/cm$^2$ for 4–6 ring PAHs. These blank values were significantly less than the concentrations of each compound in all samples used.

### *Production Quantity of RSS*

The quantity of RSS produced per day is the most important factor, since this indicates the quantity of rubber-wood used in the burning, and the corresponding smoke emission and the workers' daily work routine. This changes seasonally due to customer demand, price, the biological activity of rubber trees and level of precipitation during latex tapping. The quantity of RSS produced decreases during periods of rain fall, because farmers cannot tap the latex, the quality of which would deteriorate when mixed with precipitation. During the peak summer season (March–April), farmers stop tapping because the

**Table 2.** Particulate sampling methods and conditions.

| Factory | Coop-1 | Coop-2 | Coop-3 | Coop-4 |
|---|---|---|---|---|
| location (district, province) | Muang, Songkhla | Bangklam, Songkhla | Sadao, Songkhla | Khaochaison, Phattalung |
| Model | new | new | old | old + new |
| High volume sampler (HV) | Yes | No | No | No |
| sampling duration | 12 hr. | | | |
| sampling period | Jan. 06–Dec. 06 | | | |
| Andersen sampler (AN) | Yes | Yes | Yes | Yes |
| sampling duration | 6–14 days | 5 days | 6 days | 5 days |
| sampling period | Nov. 06, Dec.06, Feb. 08 | Jan. 08 | Feb. 08 | Feb. 08 |
| Worker's breathing zone | Yes | Yes | Yes | Yes |
| sampling duration | 6–8 hr. | ~6 hr. | ~6 hr. | ~6 hr. |
| sampling period | Aug. 06–Jul. 07 | Sep. 07–Feb. 08 | Sep. 07–Feb. 08 | Mar .07–Feb. 08 |
| Workplace by personal air sampler | Yes | Yes | Yes | Yes |
| sampling duration | 8–24 hr. | ~24 hr. | ~24 hr. | 8–24 hr. |
| sampling period | Aug. 06–Jul. 07 | Sep. 07–Feb. 08 | Sep. 07–Feb. 08 | Mar. 07–Feb. 08 |

productivity of the latex from rubber trees reaches its lowest level during the leaf-falling period due to their biological activity (Office of the Rubber Replanting Aid Fund, 2008; Tekasakul *et al.*, 2008).

### *Meteorological Data*

Although a weather station was not installed at the factories studies, meteorological conditions, such as wind direction and speed were obtained from the meteorological station in the nearby city of Hat Yai (Khohong Meteorological Station, Songkhla Rubber Research Institute, Khohong, Hat Yai, Songkhla, 7°01'N, 100°30'E) to discuss the possible influence of wind direction and speed on the workplace environment inside the factory, which has opened structures and may be influenced by outside conditions.

## RESULTS AND DISCUSSION

### *RSS Production Quantity*

Monthly changes in the quantity of RSS produced at Coop-1 is shown in Fig. 3. In the same manner as in the previous report (Tekasakul *et al.*, 2008), there is a seasonal change due to the reasons described above. The production is typically highest in January-February and the lowest in April. The decrease in production in October-December is due to precipitation, for the reasons described in the preceding section.

### *Workplace Aerosol*

#### *Size Distribution and Concentration of Particulate Matters*

The average cumulative under size fraction of airborne particles on a mass basis in the workplace sampled at Position-3 in Coop-1 ($n = 3$) is shown in Fig. 4 along with corresponding values for ambient particles in suburban Hat Yai and smoke particles from rubber wood burning (Tekasakul *et al.*, 2008). In the workplace, the 50% cumulative mass faction is approximately 1.0 μm and the size distribution may be approximated by a bi-modal log-normal distribution where the median diameters for each mode are 0.55 μm ($\sigma_g$ = 1.74) and 5.05 μm ($\sigma_g$ = 2.49),

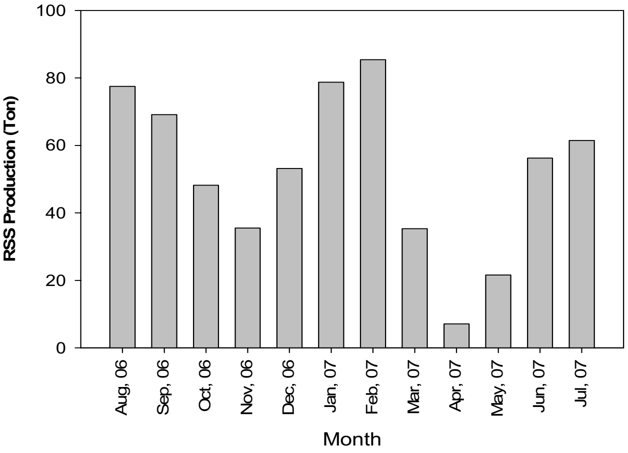

**Fig. 3.** Monthly RSS production of Coop-1.

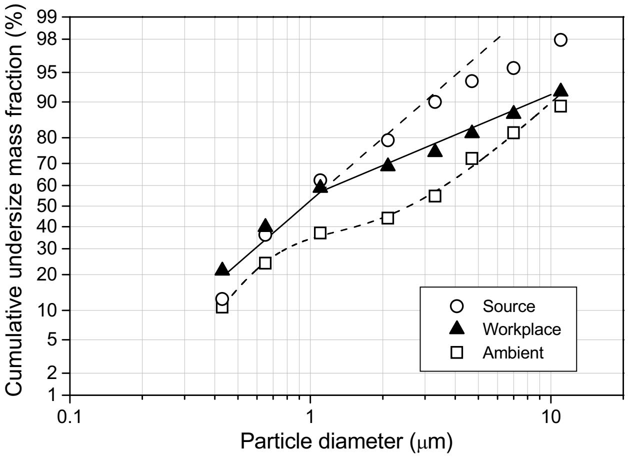

**Fig. 4.** Average cumulative under size fraction of airborne particles on a mass basis in the workplace sampled at Position-3 in Coop-1.

respectively. However, the size distribution of smoke particles from wood burning shows a rather single modal behavior with a mass median aerodynamic diameter of 0.85 µm ($\sigma_g$ = 2.46). The distribution of the smaller particles is similar to that of smoke particles and that for coarser particles is likely to approach that for ambient particles, indicating that airborne particles in the workplace are slightly influenced by ambient air from outside the factory flowing through open sections.

The monthly average total particle concentration at a workers' breathing zone is shown in Fig. 5 along with the concentrations at fixed locations. This will be discussed below in "***Exposure to smoke aerosol particles***." There is a seasonal change in the total concentration, which parallels the amount of RSS produced. There is also a variation in the total concentration due to the sampling positions in the workplace area. The total concentration at Positions-1&2 reaches a peaked during the highest production period from January to February 2007 (0.19–0.25 mg/m$^3$). It is also high in the period after May 2007 (Jun–July) and becomes lowest in the lowest production month of April 2007 (< 0.02 mg/m$^3$). The highest, lowest and yearly average total concentrations at different positions are summarized in Table 3. The highest concentrations were found at Position-3, which is located near the front door of smoke rooms, in comparison to those at other workplace positions (Position-1 and Position-2). It should be noted that data from the Andersen cascade impactor at Position-3 corresponds to the seasonal average during the high season of RSS production (November, December and February), while those from the high volume air sampler denote yearly averages. Smoke particles that enter via the front door of the smoke rooms could contribute to the high concentrations. Smoke particles that enter via the front door of the smoke rooms could contribute to the high concentrations. As discussed below, ventilation by outside wind became less effective during the months of January, February and May and the particle concentration increased during these months because of the presence of stagnant smoke inside the factory building. Under this situation, the ventilation may be more frequent at Position-3 than on the floor since it is located near the entrance for latex receiving. The maximum value of 0.30 mg/m$^3$ is still below the recommended value for occupational exposure limits (15 mg/m$^3$ (THAI regulation) and 8 mg/m$^3$ (JSOH) for total dust and 2 mg/m$^3$ (JSOH) and 5 mg/m$^3$ (THAI regulation) for respirable dust) (Thailand Ministry of Labor, 1977; JSOH, 2000). The lowest value, found in April, is similar to the ambient particulate concentration in the rural part of Hat Yai city nearby in the corresponding season (Furuuchi *et al.*, 2006).

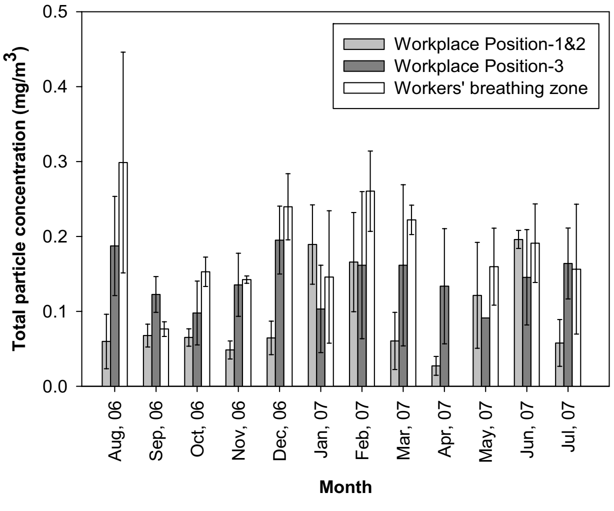

**Fig. 5.** Monthly averaged total particle concentrations in the workplace of Coop-1 at Position-1&2, Position-3, and workers' breathing zone.

The relations between the average monthly total particle concentration in the workplace positions and quantity of RSS produced in Coop-1 are shown in Fig. 6. Since Position-1 and Position-2 represent workplace locations, the average values at these positions (labeled as workplace Position-1&2) were used in comparison to those at Position-3 which is located near the smoke rooms and the entrance of the factory at the latex receiving platform. The results show that the concentrations at Position-3 are higher than those on the floor area (Position-1&2). This is because Position-3 is located near the smoke rooms which are the major source of smoke particles and which continuously leak into the workplace area through the front doors of the rooms, as described above. Moreover, the higher elevation of Position-3 may contribute to the higher concentration of smoke particles at this position because the source of smoke particles is located at the roof of the smoke room. It is more difficult for aerosol particles to travel to the lower position. The concentration of smoke particles tends to linearly increase with a similar slope with the volume of RSS production both at Positions-1, 2 and 3 although the plots are somewhat scattered. One of the reasons for the scattered data may be the influence of wind from outside as described below.

The factory building has a semi-open structure, which is widely open from the West to the Southeast direction as shown in Fig. 1. Although this opened area is the major route of smoke escape from the factory, a portion of the contaminated air can flow inside as well. Therefore, an inflowing wind can affect the ventilation of smoke particles in the factory. Fig. 7 shows the monthly average direction of the wind vector during the sampling period. The magnitude of the velocity is expressed in terms of the average wind velocity, which is directly related to the amount of ventilated air. Southwest monsoons are predominant during July–September while other directions between north and east are predominant during November–April. During transient seasons, or, in October, May and June, the wind is rather calm and its direction is not so constant, where an average monthly wind velocity less than 0.1 m/s is classified as “calm”. Hence, during the period July to September, the wind generally blows into the workplace through the large openings mentioned above. The total particle concentrations are plotted in Fig. 8 in relation to the ratio of monthly RSS production to the

**Table 3.** Concentration of particulate matter and total PAHs at different sampling positions in four RSS factories along with reported PAH concentrations.

| Factory | Coop-1 | Coop-2 | Coop-3 | Coop-4 |
|---|---|---|---|---|
| Location (district, province) | Muang, Songkhla | Bangklam, Songkhla | Sadao, Songkhla | Khaochaison, |
| Model | new | new | old | old + new |
| Particle concentration, Average ± SD., mg/m$^3$ (min–max) | | | | |
| Position-1&2 | 0.09 ± 0.07 | 0.13 ± 0.07 | 0.09 ± 0.04 | 0.13 ± 0.05 |
| | (0.01–0.26) | (0.02–0.24) | (0.03–0.15) | (0.07–0.23) |
| | n = 47 | n = 9 | n = 8 | n = 12 |
| Position-3 (HV) | 0.15 ± 0.07 | | | |
| | (0.04–0.30) | | | |
| | n = 45 | | | |
| Position-3 (AN) | 0.14 ± 0.07 | 0.21 | 0.15 | 0.12 |
| | (0.10–0.22) | | | |
| | n = 3 | n = 1 | n = 1 | n = 1 |
| Worker's breathing zone | 0.17 ± 0.1 | 0.20 ± 0.1 | 0.18 ± 0.05 | 0.29 ± 0.13 |
| | (0.01–0.40) | (0.07–0.32) | (0.13–0.23) | (0.12–0.56) |
| | n = 30 | n = 5 | n = 3 | n = 7 |
| Total PAHs concentration , average ± SD., ng/m$^3$, (min–max) | | | | |
| Position-1&2 | 97. 4± 129 | 231 ± 135 | 77.4 ± 31.7 | 98.8 ± 93.9 |
| | (15.2–775) | (91.5–463) | (26.0–114) | (16.3–319) |
| | n = 39 | n = 9 | n = 8 | n = 10 |
| Position-3 (HV) | 107 ± 87.8 | | | |
| | (1.50–283) | | | |
| | n = 31 | | | |
| Position-3 (AN) | 290 ± 335 | 422 | 150 | 64.2 |
| | (56.5–674) | | | |
| | n = 3 | n = 1 | n = 1 | n = 1 |
| Worker's breathing zone | 142 ± 184 | - | - | 246 ± 256 |
| | (9.28–650) | - | - | (25.8–607) |
| | n = 27 | - | - | n = 7 |

PAH concentrations from references

| Studied cases | workplace | | worker's breathing zone | |
|---|---|---|---|---|
| | PAHs (ng/m$^3$) | BaP$_{TEQ}$ (ng/m$^3$) | PAHs (ng/m$^3$) | BaP$_{TEQ}$ (ng/m$^3$) |
| Asphalt | - | - | 0.03–426 (g + p) | - |
| Aluminum reduction plant | - | - | 0.57–1.7 (p) | - |
| Electrode paste plant | - | - | 2.0–10.6 (p) | - |
| Sinter plant | 42–365 (p) | 3–39 (p) | 0.70–23.3 (p) | 4–137 (p) |
| Carbon black plant | 4.95–612 (p) | 0.22–1.23 (p) | 384–5622 (p) | 314–566 (p) |
| Silicon carbide plant | - | - | 700 (g + p) | 69.6 (g + p) |
| Metal recycling plant | - | - | 1423 (g + p) | 40.0(g + p) |
| Paving bitumen | - | - | 2664 (g + p) | 21.2 (g + p) |
| Graphite plant | - | - | - | 306 (g + p) |

g: gaseous phase, p: particle phase

monthly averaged wind speed. This ratio can be a measure of the possible smoke concentration inside an RSS factory contaminated by smoke emission sources and ventilated by the outside wind. There is a linear correlation between the particle concentration and the production amount/wind velocity ratio regardless to the wind direction, suggesting the importance of the amount of ventilated air by the outside wind. However, data from January and February, 2007 are deviate somewhat from this relation and show quite high concentrations even for the expected large amounts of air ventilation corresponding to the largest average wind velocity (1.4–1.8 m/s). As shown in Fig. 7, the wind direction was *E* and *E-N-E* respectively in January and February. Since these directions impact a closed side of the factory building without any open area, the wind could not ventilate the workplace inside the factory building in spite of the high wind velocity.

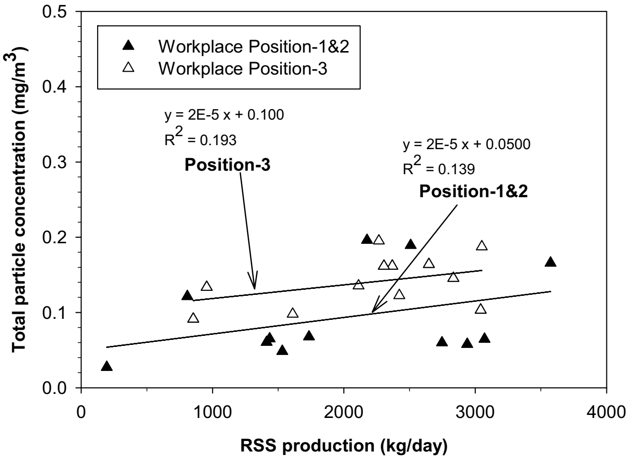

**Fig. 6.** Comparison of total particle concentration at different positions in Coop-1 in relation to RSS production.

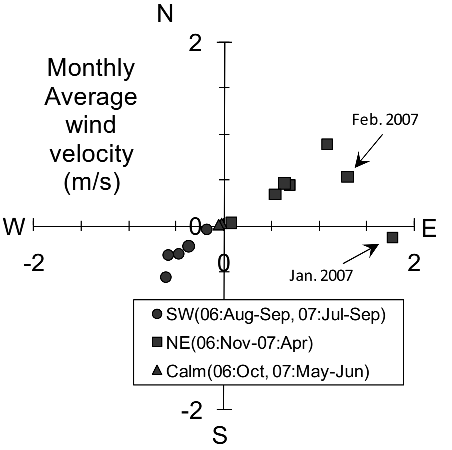

**Fig. 7.** Monthly averaged wind vector distribution in Hat Yai 2006–2007.

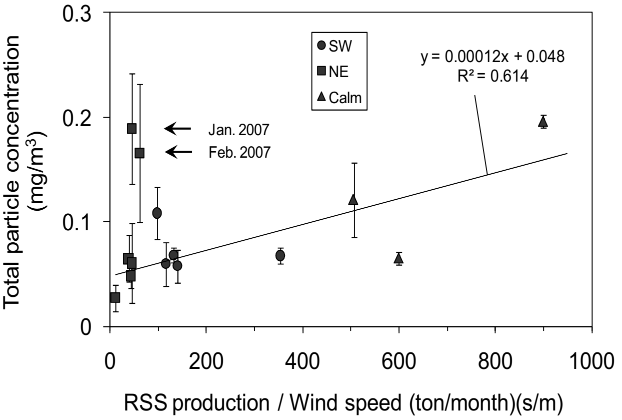

**Fig. 8.** Monthly average total particle concentration in the workplace in relation to the ratio of RSS production to average wind velocity, where a linear regression is for data except Jan. and Feb. 2007.

### *Concentration of Particle-Bound PAHs*

The yearly average concentrations of the total particle-bound PAHs were 97.4 ± 129 and 107 ± 87.8 ng/m$^3$, respectively, at the ground floor (Position-1&2) and near the smoke rooms (Position-3). Although the average PAHs concentration at Position-3 is not very high, as a place where more smoke exits from the smoke rooms, the maximum PAH concentration (775 ng/m$^3$) was obtained here during the high production period (See Table 2 and 3). These concentrations fall in the range of those in a sinter plant (42 ± 23–365 ± 203 ng/m$^3$) (Lin *et al.*, 2008) and in a carbon black manufacturing factory (4.95–612 ng/m$^3$) (Tsai *et al.*, 2002) when only particulate-phase PAHs are compared.

Taking into account that the rather high concentration of carcinogenic Benzo[a]pyrene (BaP) ranging from 26.2–34.5 ng/m$^3$ as the average values from all positions, the BaP toxic equivalent concentration, BaP$_{\mathrm{TEQ}}$, was evaluated using currently available toxic equivalent coefficients (Larsen and Larsen, 1998; Nisbet and Lagoy, 1992) as shown in Table 4. The average particle-bound BaP$_{\mathrm{TEQ}}$ concentration in Coop-1 (25.4–91.0 ng/m$^3$) is similar to that in a sinter plant (3–39 ng/m$^3$ (particle), 40–160 ng/m$^3$ (particle + gas)) as reported by Lin *et al.* (2008). It should be noted that, however, that the mass fraction of PAHs in particles (0.30 BaP$_{\mathrm{TEQ}}$ ng/μg) in the RSS factory are much higher than those in a carbon black plant (0.004–0.01 BaP$_{\mathrm{TEQ}}$ ng/μg) (Tsai *et al.*, 2002) and in a sinter plant (0.008–0.042 BaP$_{\mathrm{TEQ}}$ ng/μg) (Lin *et al.*, 2008). This is due to the nature of biomass fuel, which emits more PAHs than other fuels particularly under poor burning conditions like those in the burners of the RSS factory (Chomanee *et al.*, 2009) as reported so far and the BaP$_{\mathrm{TEQ}}$ mass fraction is consistent with values reported for residential wood combustion (McDonald *et al.*, 2000). Since the dust concentration is rather high in a carbon black plant (0.05–2.04 mg/m$^3$) (Tsai *et al.*, 2002) and in a sinter plant (0.14–2.69 mg/m$^3$) (Lin *et al.*, 2008), the mass fraction of BaP$_{\mathrm{TEQ}}$ is not as high as the RSS factory.

The monthly averaged PAH concentrations at Position-1&2 are shown in Fig. 9 along with those from Postion-3 and the workers' breathing zone. It should be noted that the values at Position-3 from February to July 2006 were used as representative for those in the same period of 2007, since samplings in this period were not conducted. The seasonal change in PAH concentration is in agreement with particle concentration shown in Fig. 5 although an increase in PAH concentration during the highest production season (January and February) was clearer. Similar to the particle concentration, the PAH concentration at Position-3 was higher than that in other locations in most cases although its fluctuation increased and sometimes became lower than that foe the floor during less effective ventilation periods such as in January, February and May. A comparison of PAH concentrations at the workplace positions is shown in Fig. 10 in relation to RSS production. The PAH concentrations at Position-3 are higher than those at Position-1&2 as in the case of particle concentration, though the trends are not striking. They also increased with RSS production. This indicates the direct influence of smoke particles from wood burning to the workplace area.

**Table 4.** Benzo(a)pyrene (BaP) concentrations (average ± SD) and total BaP toxic equivalent concentrations ($BaP_{TEQ}$) in RSS factories, ng/m$^3$.

| Factory | Coop-1 | Coop-2 | Coop-3 | Coop-4 |
|---|---|---|---|---|
| Location (district, province) | Muang, Songkhla | Bangklam, Songkhla | Sadao, Songkhla | Khaochaison, Phatthalung |
| Position-1 and 2 | | | | |
| BaP | 29.2 ± 56.7 | 43.1 ± 35.1 | 11.6 ± 7.97 | 21.2 ± 25.1 |
| $BaP_{TEQ}$ | 25.4 | 56.7 | 14.5 | 26.8 |
| Position-3 | | | | |
| BaP (HV) | 34.5 ± 37.6 | - | - | - |
| $BaP_{TEQ}$ | 39.3 | | | |
| BaP (AN) | 26.2 ± 21.1 | - | - | - |
| $BaP_{TEQ}$ | 91.0 | | | |
| Worker's breathing zone | | | | |
| BaP | 27.9 ± 26.7 | - | - | 63.7 ± 80.1 |
| $BaP_{TEQ}$ | 21.4 | - | - | 75.2 |

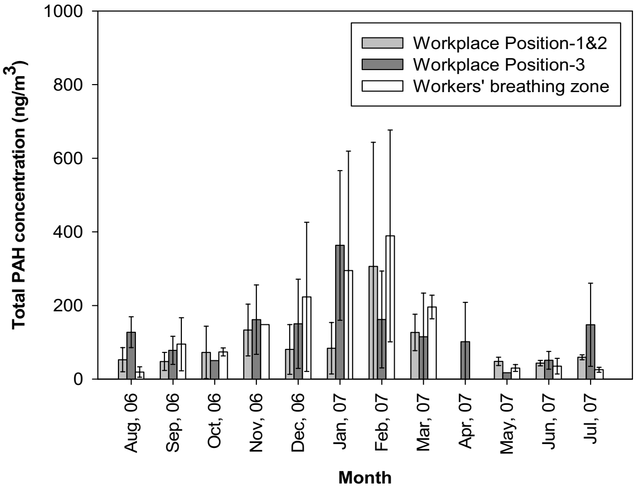

**Fig. 9.** Monthly averaged total PAH concentrations in the workplace of Coop-1 at Position-1&2, Position-3, and workers' breathing zone.

An example of the total and 4–6 ring PAHs mass ratios in size fractionated particles sampled at Position-3 is shown in Fig. 11. PAHs in particles below 3.3 µm account for more than 99% of the total PAHs and the more carcinogenic PAHs with 4–6 aromatic rings. Such enrichment of fine particles in PAHs may be due to the nature of smoke particles, which is the main fraction of fine to ultrafine particles in the workplace although a minor contribution from ambient fine particles should be included. More than 90 % of the smoke particles were smaller than 3.3 µm (see Fig. 4) and more than 99% of the PAHs are included in smoke particles smaller than ~2 µm (Furuuchi *et al.*, 2006; Chomanee *et al.*, 2009). The contribution from ultrafine particles (< 0.43 µm) is about 18%. This may be important regarding the effects of PAHs on general health, since all particles in this size range are classified as respirable particles less than 5 µm as defined by the British Medical Research Council (The SafetyLine Institute, 2009).

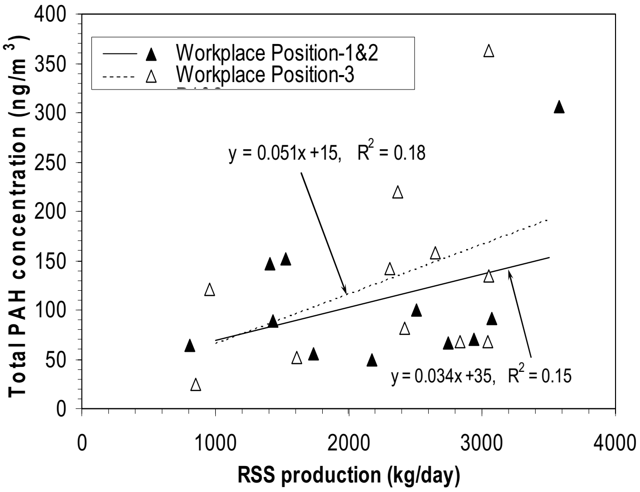

**Fig. 10.** Comparison of total PAH concentration at different positions in Coop-1 in relation to RSS production.

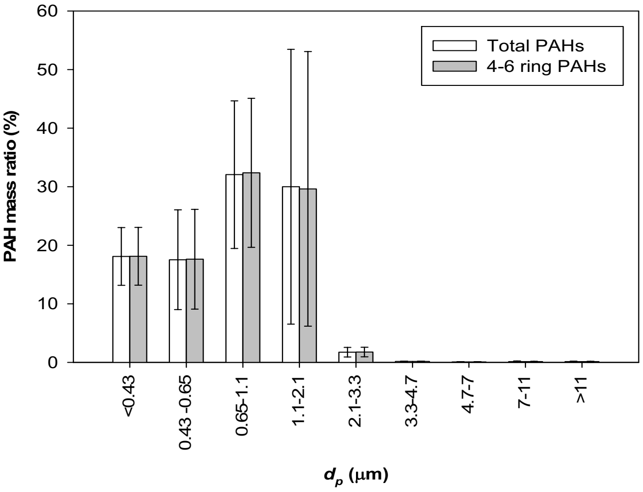

**Fig. 11.** Size distributions of total and 4–6 ring PAHs in terms of mass ratio.

From the characteristics of particulates described above, it can be concluded that the workplace environment in the RSS factory, which is always contaminated by fine smoke particles from biomass burning, constitutes a rather high potential health risk of exposure to carcinogenic PAHs to workers, even if the particle concentration is lower than regulations. Moreover, the total exposure risk in an RSS factory should increase by 3–4 times compared with other factories with similar $BaP_{TEQ}$ concentrations, since the workers are exposed 24 hours a day throughout the year.

### *Workers' Exposure*

#### *Exposure to Smoke Aerosol Particles*

The average monthly personal exposure to PAHs of workers is also shown against the amount of RSS produced (Fig. 10) along with the particle concentration in the workplace (Position-1&2). Similar to the particle concentration in the workplace, the personal exposure is increased with RSS production; the highest concentration occurred in August 2006 (0.30 ± 0.15 mg/m$^3$) and the lowest was in July 2007 (0.06 ± 0.04 mg/m$^3$).

The concentrations of particles inhaled by workers in the breathing zone around the sampler inlet at the worker's collar during the sampling period showed distinctively higher values than those at fixed sampling points on the floor (Position-1&2. See Fig. 1). The concentrations in the workers' breathing zone are approximately double those at Positions-1&2 and are increased when RSS production is increased as well. The particle concentration in the worker's breathing zone, averaged for the entire period (0.17 ± 0.1 mg/m$^3$) was about twice as high as the corresponding workplace concentration (0.09 ± 0.07 mg/m$^3$) although these concentration were still below the regulation values. This is probably because the workers were exposed to concentrated smoke in the smoke room when they entered the smoke rooms to load the rubber hanging truck and to periodically check the quality of the rubber sheets, e.g., ~200 mg/m$^3$ (Furuuchi *et al.*, 2006), although they sometimes stayed outside the factory.

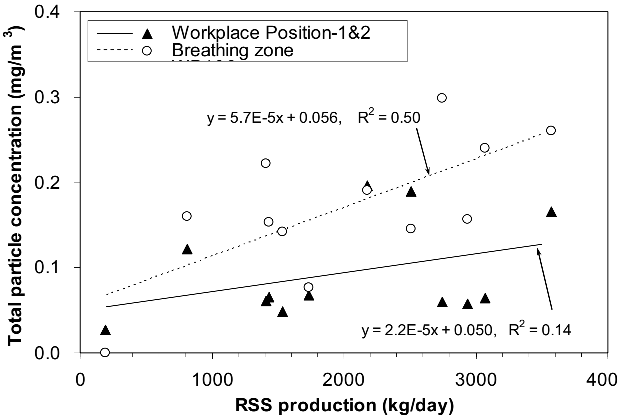

**Fig. 12.** Comparison of total particle concentration between stationary workplace positions (Position-1&2) and workers' breathing zone in Coop-1.

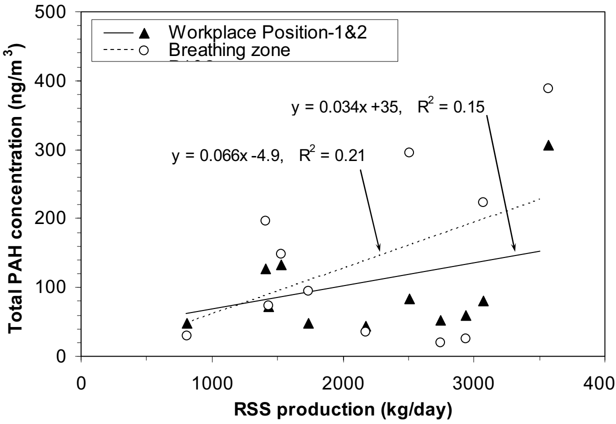

**Fig. 13.** Comparison of total PAH concentration between stationary workplace positions (Position-1&2) and workers' breathing zone in Coop-1.

#### *Particle-Bound PAH Exposure*

The relation between the average monthly total PAHs concentrations in the workers' breathing zone and RSS production is shown in Fig. 13 along with those at workplace Position-1&2 for comparison. It should be noted that the workers exposure was evaluated only for the period that they were on duty, although most workers living in the factory are exposed to smoke particles even during their off duty time. Both concentrations increased with increasing RSS production particularly when production exceeded 3000 kg/day. This may be due to the wind direction during the largest production period to the closed side of the factory building as described earlier. Although, in many cases, PAHs concentration in the breathing zone was higher than that in the workplace, the trends were not so clear. This may be due to the worker's job characteristics such that they experience both concentrated smoke particles inside the drying room and the fresh air outside the factory building. Similar to the workplace environment, the average exposed total PAHs concentration of workers in Coop-1 (142 ± 184 ng/m$^3$) is between that for a sinter plant (0.7–23.3 ng/m$^3$) (Lin *et al.*, 2008) and a carbon black manufacturing factory (384–5622 ng/m$^3$) (Tsai *et al.*, 2001). The corresponding average $BaP_{TEQ}$ concentration (21.4 ng/m$^3$) is in the same order as workers in a paving bitumen (21.2 ng/m$^3$ (particle + gas)) and a metal recycling plant (40.0 ng/m$^3$ (particle + gas)) (Petry *et al.*, 1996) but it is lower than that for police officers controlling road traffic in China (82.1 ng/m$^3$) (Liu *et al.*, 2007), tollbooth attendance (151–230 ng/m$^3$) (Tsai *et al.*, 2004), carbon black plant workers (314 and 566 ng/m$^3$) (Tsai *et al.*, 2001), silicon carbide plant workers (69.6 ng/m$^3$) and graphite plant workers (306 ng/m$^3$ (particle + gas)) (Petry *et al.*, 1996). Although the workers are not exposed to direct smoke in the workplace after finishing their daily duties around 5 PM, they constantly inhale some smoke particles because they reside in a section next to the workplace area in the factory. Their total $BaP_{TEQ}$ exposed amount can be roughly estimated to be 2–3 times as high as that obtained during an 8-hour period of work.

### *Effect of Ventilation on Particulates and PAHs Concentration*

Fig. 14 shows the relation between the amount of RSS produced and average total particle concentration in corresponding periods measured at sampling sites similarly arranged on the floor in the four different factories shown in Fig. 2. The average concentrations of total particle concentration and PAHs are summarized in Table 3. Although the data are somewhat scattered, the concentration increased with production, regardless of the building geometry and the type of ventilation facilities used. However, there are differences in the slope for both particle and PAH concentrations. This is particularly true in Coop-3, probably because of the insufficient area of the open sides of the building. Roof turbines in Coop-3 were not sufficient to cover a lack of air ventilation by the monsoon wind. The roof ridge vent used in Coop-4 was confirmed to smoothly ventilate the smoke from the smoke rooms to the outside and provided a similar situation on particle and PAH concentrations to that in Coop-1 in spite of the fact that less area of the open sides faced the monsoon wind. This suggests a slight improvement in air ventilation by the roof ridge. As previously discussed, the location of the factory building in relation to the monsoon wind is quite important for the achieving effective ventilation. Ideally, the factory building should be constructed with its large open sides facing SW and NE although there are no current plans for constructing new cooperatives. Concerning Coop-1, making small openings between the roof and side wall on the east side of the building, similar to the north side would be expected to significantly improve overall ventilation. To have openings facing in the monsoon direction is commonly effective in all types of cooperatives. However, this is difficult in some cases. For these cases, roof ventilation is another option but more information related to roof ventilating turbines or roof ridge vents may be needed for effective natural ventilation. In addition, smoke particle removal devices could be implemented. Although forced ventilation or the filtration of smoke particles may be possible using external fans, this will burden the cooperative with an extra cost. The most viable technique for reducing PAH levels may be by the introduction of an electrostatic precipitator as previously investigated for RSS production (Tekasakul *et al.*, 2006) and which is currently undergoing further modification.

## CONCLUSION

The workplace environment in factories producing ribbed smoked sheet rubber (RSS) in southern Thailand, the insides of which are heavily contaminated by wood burning smoke, has been evaluated with a focus on the workplace concentration of smoke particulates and particle-bound PAHs as well as their exposure to workers in the breathing zone. Seasonal changes in particulates and PAH concentrations were discussed in relation to the amounts of RSS produced, and the direction and speed of the wind. Based on particulate concentrations measured in factories with different types of ventilation facilities, the influences of ventilation type and factory building geometry were also discussed.

Results derived from the investigation can be summarized as follows:

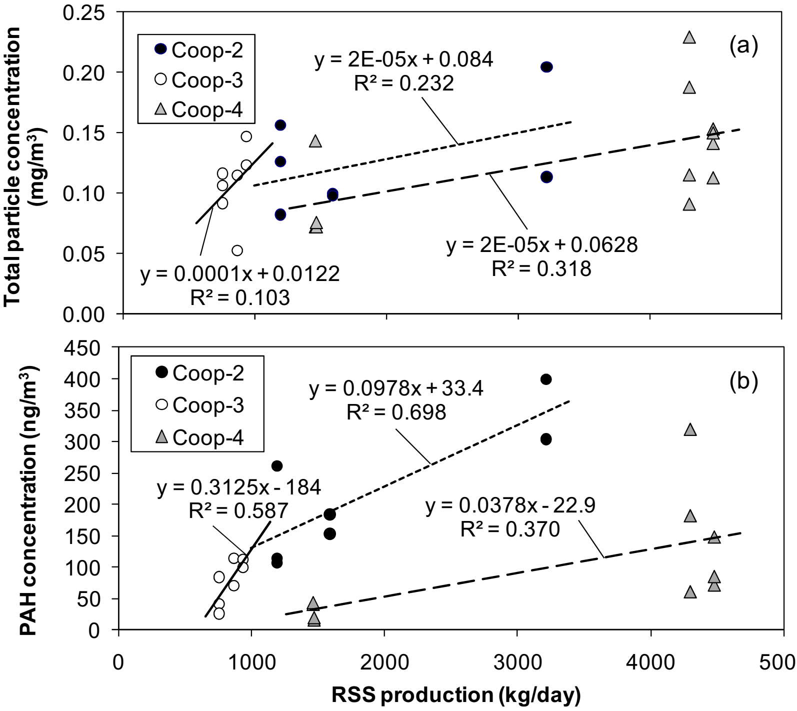

**Fig. 14.** (a) Total particle concentrations of all stationary samplings in three RSS factories and (b) PAH concentration in relation to RSS production.

1. The particle concentration in the workplace increased nearly linearly with RSS production. However, the amount of ventilated air was also shown to be important in reducing particle concentration, particularly during the season when the open sides of the building face in the monsoon wind direction, i.e., SW and NE.
2. Particle concentrations in the workers' breathing zone are double those in the workplace because the workers inhale additional smoke particles by periodically working in the smoke rooms. However, the concentrations in the workplace and in the worker's breathing zone are somewhat lower than common occupational exposure limits (e.g., 15 mg/m$^3$ (THAI regulation) and 8 mg/m$^3$ (JSOH) for total dust).
3. Rather high average total PAHs concentrations of 97.4 ± 129 ng/m$^3$ and 142±184 ng/m$^3$ were found in the workplace and in the breathing zone, respectively. This is probably related to the large mass fraction of PAHs in smoke particles derived from biomass burning.
4. Rather high $BaP_{TEQ}$ concentrations, both in the workplace and in the breathing zone exposure may lead to a rather high health risk from PAHs exposure to workers in the RSS factory.
5. Natural ventilation by roof turbines was confirmed to be insufficient in terms of reducing PAHs levels although roof ridge vents slightly improved the ventilation in the present case. A factory design that takes the monsoon wind direction into account may be essential for achieving effective ventilation with minimal cost.

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