



Improvement Soot Particles Separation Equipments for Rubber Smoking Chamber

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ABSTRACT

Soot produced from rubber tree wood combustion during the process of drying natural rubber sheets has been shown to produce negative health effects for workers, as well as poorer quality rubber sheets. This study examined ways to improve soot particle separation equipment for rubber smoking chambers. An impaction wall was able to catch all soot particles ranging in size from 3.3-4.7 microns and a modified electrostatic precipitator, installed outside of the rubber smoking chamber in order to decrease danger to workers and with the highest available voltage supply of 12 kV, captured soot particles 0.43-3.3 microns in size. This modified precipitator operated longer than the usual time 120 hours or more before requiring cleaning; equivalent to smoking about 12 lots of rubber sheets or operating for 3 months during high rubber production season. The total efficiency of soot particle separation through the use of the modified collection equipment was more than 50% for all tests. In addition, the color index of rubber sheets used in the testing improved from 6.0 to 12.0. Coloration, which is a measure of quality, was better than sheets from smoking chamber lacking soot particle separation equipment.

Keywords: Soot particles; Rubber wood combustion; Natural rubber sheet drying.

INTRODUCTION

Soot particles are produced from incomplete combustion of carbonaceous materials (Ndiema *et al.*, 1998), including wood combustion for drying agriculture products, such as natural rubber (*Hevea brasiliensis*) sheets in Thailand. Soot emitted during the rubber drying process produces environmental and human health problems, such as pulmonary diseases and cardiovascular illness. Thailand has the largest natural rubber (NR) production and export in the world. The total amount of natural rubber production in 2006 was about 3.2 million metric tons (Thailand Rubber Research Institute, 2007). About 90% of the NR produced was exported. Generally, most natural rubber products are used in vehicle tire production; hence, the direction of NR production follows consumption in the world market. The amount of NR exported from Thailand in the last three years has increased about 0.2 million tons per year; however, the increasing quantity is insufficient for the growth of the tire industry. In the coming years, it is expected that NR production will double. To meet these expectations, while also limiting atmospheric and human health impacts, improvement of NR production for 7 million Thai farmers (particularly in southern Thailand) must be carefully planned and implemented.

Natural rubber in Thailand is produced in four types; ribbed smoked sheet (RSS), block rubber, rubber concentrated latex, and miscellaneous other forms. The proportion of each type is 35%, 35%, 28% and 2%, respectively. Production of each type depends on the world's NR consumption. In the world's rubber market, the United States, Japan, China and India are the largest consumers, while Japan and China (Tekasakul *et al.*, 2008) are Thailand's largest exporting markets. At present, the worldwide

consumption of rubber-concentrated latex is nearly constant. In contrast, both RSS and block rubber consumption is increasing due to increasing demands of the rubber tire industry.

In RSS production, Thailand can produce from July to March, while December to February is the high season. In the rubber smoking process, sheets of rubber are washed in a pool and hung on bamboo bars for drying before transferring to smoking chambers where rubber-tree wood is burned as a heat supply to reduce the moisture content in the sheets. In this process, wood burning produces wastes, such as carbon, water vapor, ash residue, and soot particles. Soot particles in the rubber smoking chamber produced from wood combustion have negative effects for the workplace environment, on worker health and also in quality of the rubber sheets themselves. Excessive deposition of soot particles on the sheet surface results in a darker color, which is considered below market standards and thus lower prices (Kalasee, 2005). In order to reduce these problems, a method for soot particle reduction is needed. However, the gas does not require a complete cleanup before entering the rubber smoking chamber, since soot particles contain some phenolic compounds (Simonelt *et al.*, 1993) which hinder the formation of molds and bacteria that reduce the shelf life of rubber sheets. Kalasee *et al.* (2003) found that the size distribution of soot particles from rubber wood combustion in the smoking room has an average mass median aerodynamic diameter (MMAD) of 0.95 microns. The average value of geometric mean standard deviation (GSD) is 2.51. The mass concentration of the smoke particles depends on the moisture content of the fuel wood. Kalasee *et al.* (2003) also found that particle concentrations range from 47-1,358 mg/m³ for 34.5-107.5% moisture content in fuel wood.

Several methods and devices were used for particle collection to reduce or prevent emission of particles escaping into the atmosphere; e.g., filtration, centrifuged cyclones, scrubbers, gravitational settling, etc. However, these methods need large spaces for installation. Filtration induces pressure drop when filters are contaminated with particulates during long operation times. Cyclones, scrubbers and gravitational settling can capture

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large particles greater than 10 microns; however, the collection efficiency is lower for smaller particles. In this work, a corona discharge device, or an electrostatic precipitator (ESP), was used to collect soot particles with variable concentration in the submicron range. This device has the advantage of high collection efficiency and less pressure drop.

In a previous work, Kalasee (2005) and Tekasakul *et al.* (2005) found that ESP utilizing a corona discharge was suitable for catching soot particles in wood combustion systems and improving the color of drying rubber sheets in a smoking chamber. However, ESP had some negatives for tar and volatility which decreased the life of the sheets. Installing an ESP in the smoking chamber would be dangerous for the electrical system because of the high amount of waste water produced in the drying process. During the high season it is important to change and clean electrodes before operating the system; therefore, the collection equipment was newly designed for use outside of the smoking chamber. Previously, ESPs were located inside chambers.

Rubber Smoking Chamber

Most of the RSS manufacturers in Thailand are located in the south, where production is shifting from large-scale industries to community-level rubber cooperatives. About 700 cooperatives are currently operating throughout the country and each could produce about 500-1,000 metric tons per year of ribbed smoked sheets (RSS). Fig. 1 shows the rubber smoking chambers are constructed of brick and mortar, and the average chamber is $2.5 \times 6 \times 4 \text{ m}^3$ in size. The front wall is typically a steel gate for loading and unloading rubber. Ventilating windows are on the rear wall and the ceiling. The rooms are generally equipped with sensors for controlling the temperature. Heat and smoke distribution tunnels are on the floor. The rubber sheets are hung on bamboo poles placed on $2 \times 2 \times 2 \text{ m}^3$ steel crates. A forklift is used to maneuver the crates into and out of the chambers. Furnaces are located at the rear of the chambers and about 0.5 meters below the floor. Hot gas and smoke are conveyed through the distribution duct and grid into the chamber. The furnace normally has dimensions of $0.6 \times 0.6 \times 1.5 \text{ m}^3$ and is constructed from brick. Combustion rate is controlled by an adjustable steel gate in the front.

Particle Sampling Method

Soot particles are defined as all particles emitted from the combustion. Sampling was performed between the impaction wall and ESP in the tunnel which carries the combustion gas into the smoking chamber. An eight-stage Andersen Impactor (Dylec, Model AN-200) with cut sizes of 0.43, 0.65, 1.1, 2.1, 3.3, 4.7, 7.0 and 11.0 microns was used for the experiment. A backup filter was used to collect particles smaller than 0.43 microns (Tekasakul *et al.*, 2008). Prior to sampling, the sampling plates were cleaned in an ultrasonic bath, dried overnight in a desiccator, and weighted in an analytical balance (Mettler, AB 204-S). After sampling, particles were placed in the desiccator prior to weighting in the same analytical balance in order to determine the mass of collected particles.

Particle Collection Method

Although, many methods (i.e., filtration, centrifuged cyclones, scrubbers, gravitational settling, etc.) could separate out particles, they are not suitable for use in the rubber smoking chambers. For this study an electrostatic precipitator (ESP) and an impaction wall were found to be more appropriate.

Electrostatic Precipitator

An ESP is a particulate collection device which uses electrostatic force to remove or separate the particles from a gas stream. The principle is to give an electrostatic charge to particles in a gas stream and then pass the particles through an electric field that drives them to a collection electrode.

ESP requires maintenance of a high-potential difference between two electrodes, one a collecting electrode, which has a larger radius of curvature, e.g., a cylinder or a flat plate, and is electrically grounded. The discharging electrode, which has a smaller radius of curvature, e.g., thin wire or a sharp point, is held at a high voltage (Chang, 1998; Chen, 2002). Because of the high potential difference between the two electrodes, a powerful ionizing field is formed.

Every particle either has, or can be given, a positive or negative charge. If all particles in the gas stream have a negative charge and the collection plate is positively charged, the negatively charged particles will migrate to the grounded collection plate and be captured. The particles will quickly

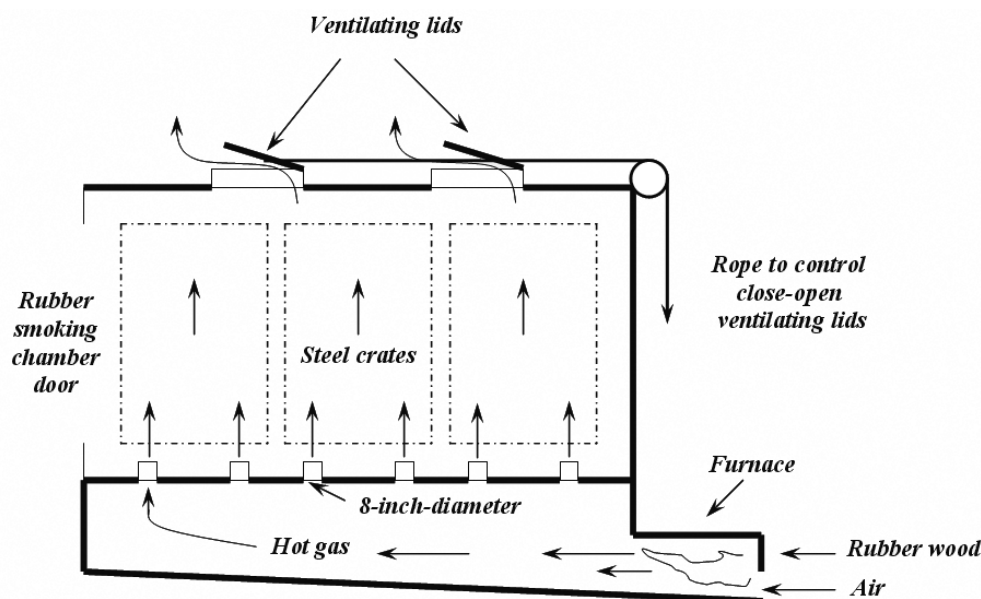


Fig. 1. Schematic diagram of the rubber smoking chamber.

deposit on the plate, and accumulate a layer of dust that is possible to remove, either by rapping or sweeping the plate, or spraying it with a liquid.

Many researchers such as: Kim and Lee (1999) Jedrusik *et al.* (2001); Laskin and Cowin (2002); Elayyan *et al.* (2002); Kulkarni *et al.* (2002); Xiangrong *et al.* (2002); Jedrusik *et al.* (2003); Fujishima *et al.* (2004); Xiangrong *et al.* (2005) and Clack (2006) considered ESP for the removal of small particles (e.g., dust, fumes, smoke, diesel exhaust and soot particles); but the expensive design and voltages above 25 kV for use in RSS manufacturing are still unsuitable since it would be too complicated for workers to operate.

Kalasee (2005) found that removing soot particles from the collection plate by spraying caused moisture content to increase, resulting in molding. This study modified an ESP by installing it between the furnace and the rubber smoking chamber to collect the soot particles before entering the rubber smoking chamber. This installation increased the life of the ESP and decreased the danger of electrocution.

Impaction Wall

The impaction wall (similar to a flat plate) is a simple collection method which uses mechanical force to remove particles from the gas stream. In principle, soot particles colliding with large inert object are able to pass from the streamline through the nozzle in front of impaction wall as shown in Fig. 2.

EXPERIMENTAL

The experiment was divided into two parts. First, a burner (Fig. 3) was built for field-testing and evaluating soot particle separation by impaction wall and a modified ESP. Then the equipment was designed for soot particle collection (Fig. 3) in an actual rubber smoking chamber.

Field Testing

In this experiment, collection efficiency and soot particle size range distribution were measured. A burner was built for this test.

Collection Efficiency of a Simple Designed Electrostatic Precipitator

For field-testing and use with a rubber smoking chamber, a

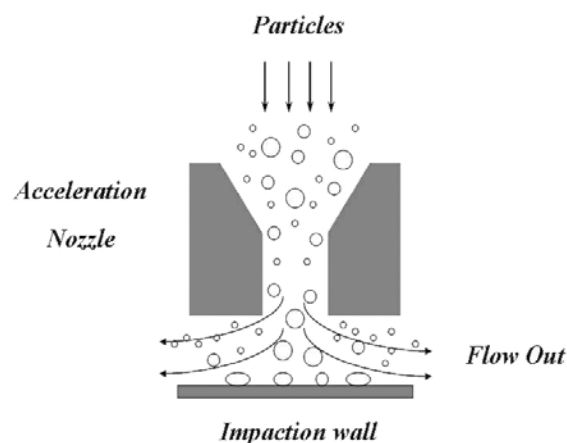


Fig. 2. Collection of particles by an impaction wall.

low-cost and simplified ESP was designed to use for collecting soot particles. The analytical expression for the efficiency of the ESP is given by the Deutsch-Anderson equation (Hinds, 1999):

$$\eta = 1 - \exp\left[-\frac{AV_e}{Q}\right] \quad (1)$$

Where A is the collector surface area, V_e the particle migration velocity, Q the volume flow rate of gas, and η is the ESP fractional collection efficiency.

The collection efficiency of ESP increases with the migration velocity. The relationship for migration velocity is given by:

$$V_e = \frac{qEC}{3\pi\mu D_p} \quad (2)$$

Where q is the electrical charge on particles, E the electric field strength, C the slip correction factor, μ the air dynamic viscosity, and D_p is the particle diameter.

Fig. 4 shows the designed ESP with a single copper wire electrode (0.5-mm-diameter, length 150 cm) placed in the middle of the ESP between two grounded, stainless steel plate electrodes.

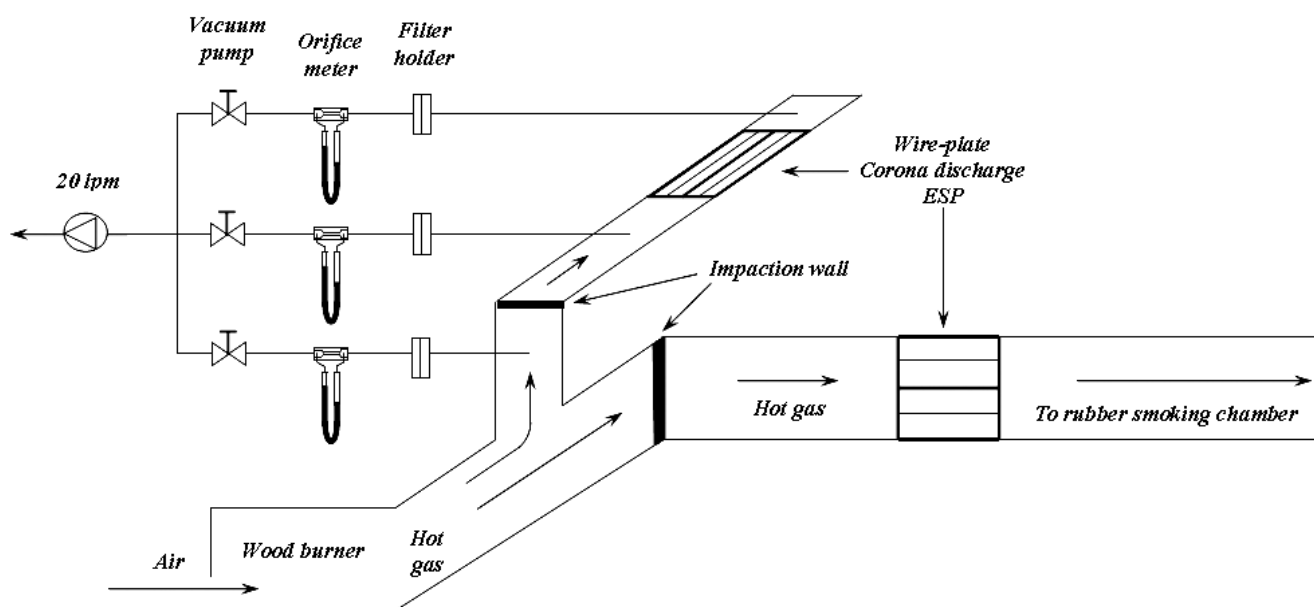


Fig. 3. Schematic diagram of field test set up.

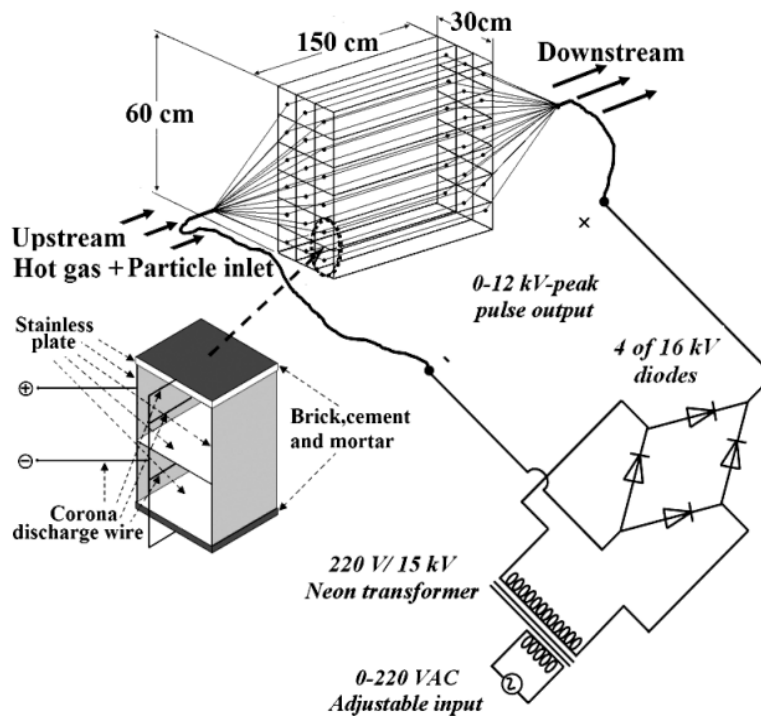


Fig. 4. Diagram of the corona discharge device and electric circuit.

The plate electrode lengths were 150 cm each; while the plate-to-plate electrode spacing was 10 cm (total spacing in the tunnel remained 30 cm width, 150 cm length, and 60 cm high). The ESP collects soot particles before the hot gas enters the smoking chamber through 12 8-inch-diameter tubes at floor level. The collecting device is connected to a simple electrical circuit that supplies a high potential difference between the electrodes. The inlet voltage of 220 V AC is adjustable with a slide regulator between 0-220 V (Chuan Hsin, SRV-10). This voltage is then transformed into high voltage (0-15 kV) by a neon transformer (LECI, EX230A15N). A Wheatstone bridge circuit consisting of four high-voltage diodes (16 kV) is used to transform the high-voltage AC current to a rippled DC current. In this work, the input operating voltage of the ESP was kept constant at 220 V which corresponded to 12 kV (Kalasee *et al.*, 2006; Srisang *et al.*, 2006) at peak output. The corona discharge wire was located at the negative electrode and the collecting electrode carried a positive charge. This simple circuit was used because it is easy to construct and affordable for the manufacturers.

Collection Efficiency of a Simply Designed Impaction Wall

For this work, the impaction system was also designed to be simple. It was installed across the flow of hot gas and soot particles between the furnace and modified ESP (primary collection). It was made from brick, concrete and mortar.

According to conventional impaction theory (for flat, rigid substrates), the dimensionless Stokes number (*Stk*) is the principle factor for impaction and is given by:

$$Stk = \frac{\rho_p D_p^2 U C_C}{9 \mu W} \quad (3)$$

Where μ is the air dynamic viscosity; W is throat width; ρ_p is particle density; D_p is particle diameter; U is air velocity in the throat; and C_C is Cunningham slip correction factor. The slip correction factor is specified by (Hinds, 1999):

$$C_C = 1 + \frac{D_p}{\lambda} (2.34 + 1.05 e^{-\frac{0.390 \lambda}{D_p}}) \quad (4)$$

Where λ is the mean air molecule free path.

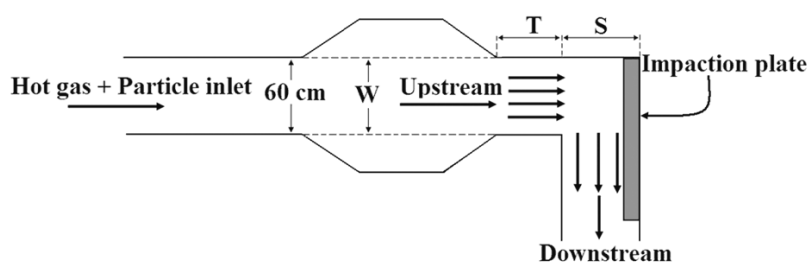
Fig. 5 shows the impaction system which consisted of a hot gas flow in the throat tunnel (stopping distance) as a rectangular acceleration nozzle and an impaction wall. In this design, the dimensions of the impaction wall were 150 cm (length) and 60 cm (high). The throat width (W) was 60 cm and its length (L) was 30 cm. The stopping distance (S) was 30 cm. The ratio of S/W was 0.5. Hence, the value of Stokes number in theory for the stopping distance was 0.5 (Hinds, 1999). The velocity range of hot gas flow in the throat tunnel was 200-500 cm/s. Its value was estimated and considered from simulation data with an air velocity inlet into the furnace by computational fluid dynamics (CFD) modified from Kalasee (2005), Promtong (2006) and Promtong and Tekasakul (2007). The collection efficiency of the impaction-wall separation of soot particles was determined by the before and after weight of the zinc plate in each test (for this design, the zinc plate is built on the impaction wall due to dust load) and this equation:

$$\eta = 1 - \frac{C_{exit}}{C_{inlet}} \quad (5)$$

Where C_{exit} and C_{inlet} are the particle concentration at the exit and inlet of the collecting device, respectively.

Soot Particle Distribution Range

In this experiment, an 8-stage Andersen impactor (Dylec, Model AN-200) replaced the filter holder as shown in Fig. 3. And the aerosol was pulled through the flue by a vacuum pump used in the preceding section. The flow rate was 28.3 L/min. These vacuum pumps were then operated only within 30 minutes for all tests. The mass of the plates was measured by a 4-digit analytical balance (Mettler, AB204-S) before and after the experiment.



Physical Characteristics of Impactor		
	W (cm)	60
Acceleration (Throat) nozzle	T (cm)	30
	S/W	0.5
Impaction plate (substrate wall)	Length (cm)	150
	High (cm)	60

Fig. 5 Schematic diagram and the physical characteristics of impactor.

Rubber Smoking Test

An impaction wall and a single modified ESP (a wire-plate type) were built for soot particle collection and replaced the earlier versions of ESP used for the rubber smoking process, which utilized 12 identical wire-cylinders. The new system was installed between the furnace and rubber smoking chamber. The impaction wall also increased the life of the modified ESP. Kalasee, (2005) and Tekasakul *et al.* (2006) operated an ESP only for 30 minutes after the introduction of fresh wood to the burner, since the smoke is at its greatest density during this period. In this study, the total operating time for testing the drying of one lot of rubber sheets using the ESP was 10 hours. During four days of processing, fresh wood combustion took place 20 times. A total of three months, or 12 lots of the rubber sheets of drying tests were performed and the modified ESP was in operation 120 hours.

RESULTS AND DISCUSSION

The results for this research are divided into four parts. In the first part, dust load and size particle collection by an impaction wall and ESP are evaluated. The second part, the life of a modified ESP is studied. The third part presents a look at soot particle distribution for the equipment. And finally, the color of the dried rubber sheets for all experiments is observed.

Dust Load and Size Particle Distribution

Table 1 shows the total particle mass concentration and the efficiency of the impaction wall. Particles from upstream and downstream of the ESP were sampled and measured. This study assumed that particles downstream of an impaction wall equalized the particles upstream of the ESP. In Table 1, runs #3, #5, and #8, as well as the total particle concentration are very high, due to the increased moisture content of the rubber tree wood, which was stored outdoors and absorbed rain water. The size-fractionated collection efficiency of soot particles for the impaction wall and ESP are shown in Figs. 6 and 7, respectively. The results show that the impaction wall has significant effect for all size of soot particles range. The quantity of large particles range from 3.3 to 4.7 microns which collected by the impaction system was higher than small particles. However, Fig. 6 shows that for a part of another curve, the small particle collection was near the large particles. It indicates that the hot gas flow in the tunnel was turbulent. So, an impaction wall also has significant influence on collecting small particles according to the Brownian motion and diffusion method.

Fig. 7 shows the influence of size particles on the collection efficiency of the designed ESP during on experiments. The small

particle amount was higher than large particles due to the influence of the Brownian motion and diffusion charging mechanism of small particles.

The collection efficiency of soot particles under dust loading of an impaction wall and ESP are shown in Figs. 8 and 9. The collection efficiency is plotted against the dust-loading parameter (cvt); where c is the particle mass concentration, v is the aerosol velocity, and t is the collection time. In Fig. 8, the collection efficiency of the impaction wall is rather constant as the particle concentration and operation time increase. This result indicates that the quantity of particles and time operation did not have significant influence. But the results for the ESP found that as particle concentration and operation time increased, the collection efficiency of the ESP decreased. This is in agreement with Chang's experiments (1998). The loading of dust on the electrode reduced the electrical interactions between the collecting surface and charged particles.

The main problems of an impaction wall are the pressure drop, and the velocity and temperature variation in the rubber smoking chamber. So, in this experiment it was necessary to control the combustion rate by using an adjustable steel gate on the front of furnace to adjust the temperature in the smoking chamber to between 50-65°C. For the rubber smoking process, the temperature was set about 49-52°C on the first day, about 52-57°C in second day, about 57-60°C the third day, about 60-63°C the fourth. Over a period of days, the temperature was constant at about 50°C, and the hot gas flow velocity constant at about 20 L/m (modified from Prasertsan, 1993; Kalasee, 2005; Tekasakul *et al.*, 2006).

Life Span of a Modified ESP

Table 1 shows the collection efficiency of the modified ESP (wire-plate) for the clean ESP electrode is decreased from 78% to 40% after operating at 7200 minutes (120 hours) or the rubber sheets 12 lots. This result is better than compared with the results from Kalasee (2005) and Tekasakul *et al.* (2006). After 120 hours of operation, the collection efficiency of this ESP design decreases and the ESP electrodes must be changed or cleaned.

Escaping Soot Particle Distribution in the Rubber Smoking Chamber

In this study, gas is not required to complete the cleanup system before entering the rubber smoking chamber, because soot particle distribution decreases about 50% of total particle production from the rubber wood combustion. Soot particles contain phenolic compounds (Simonelt *et al.*, 1993) which hinder the formation of molds and bacteria, which affect rubber sheet

Table 1. Upstream, downstream and total collection efficiency of soot particle distribution using an impaction plate and ESP.

# Run	t (min)	Impaction plate		Eff. (%)	ESP		Eff. (%)
		Upstream Particle (mg)	Downstream Particle (mg)		Upstream Particle (mg)	Downstream Particle (mg)	
1	300	2564	2153	16.03	2153	475	77.94
2	600	3208	2846	11.28	2846	859	69.82
3	900	1724	1479	14.21	1479	425	71.26
4	1200	9516	7547	20.69	7547	1859	75.37
5	1500	4632	3894	15.93	3894	1341	65.56
6	1800	2952	2549	13.65	2549	1106	56.61
7	2100	15987	12354	22.72	12354	4298	65.21
8	2400	1617	1367	15.46	1367	524	61.67
9	2700	2264	2135	19.86	2135	798	62.62
10	3000	1992	1629	18.22	1629	891	45.30
11	3300	2984	2546	14.68	2546	1143	55.11
12	3600	10258	8012	21.90	8012	3202	60.03
13	3900	5848	4725	19.20	4725	2258	52.21
14	4200	14594	11205	23.22	11205	4651	58.49
15	4500	2104	1887	10.31	1887	914	51.56
16	4800	1564	1395	10.81	1395	783	43.87
17	5100	16592	12854	22.53	12854	6141	52.22
18	5400	2789	2415	13.41	2415	1324	45.18
19	5700	1846	1527	17.28	1527	869	43.09
20	6000	13216	10248	22.46	10248	5228	48.99
21	6300	2841	2306	18.83	2306	1325	42.54
22	6600	2258	1924	14.79	1924	1143	40.59
23	6900	17243	13257	23.12	13257	6925	47.76
24	7200	3106	2678	13.78	2678	1598	40.33
25	7500	13215	10089	23.65	10089	5786	42.65
26	7800	2962	2456	17.08	2456	1856	24.43
27	8100	3521	3052	13.32	3052	2568	15.86
28	8400	3142	2554	18.71	2554	2124	16.84

Eff. is the total collection efficiency.

One lot of rubber sheet production for an impaction wall and ESP operation in this Table is every 2[#]Run times, or every 600 minutes or 10 hours.

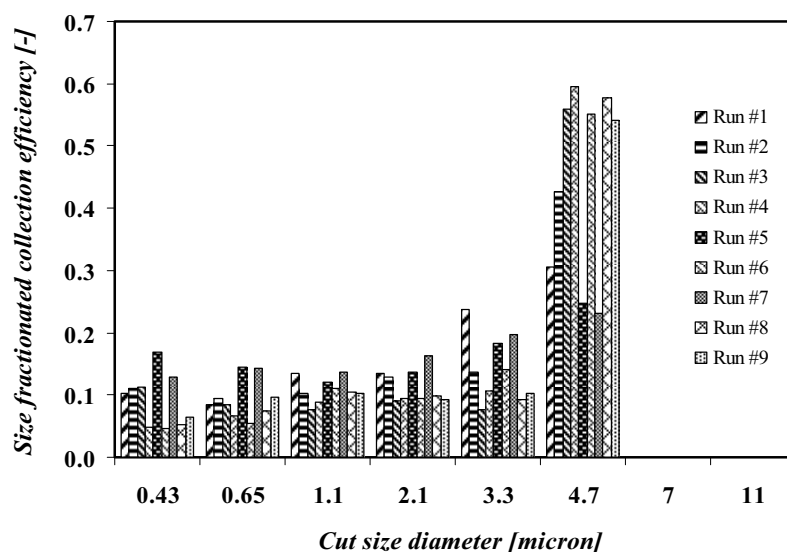


Fig. 6. Size fractionated collection efficiency of soot particles by impaction wall.

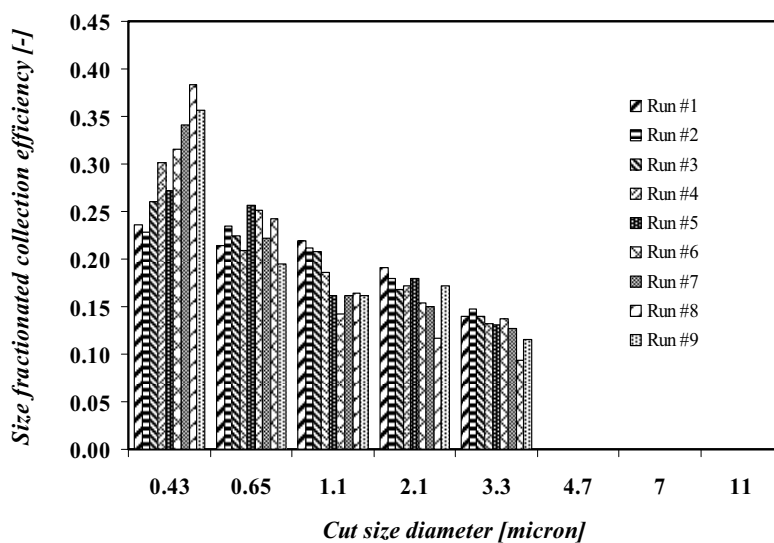


Fig. 7. Size fractionated collection efficiency of soot particles by ESP.

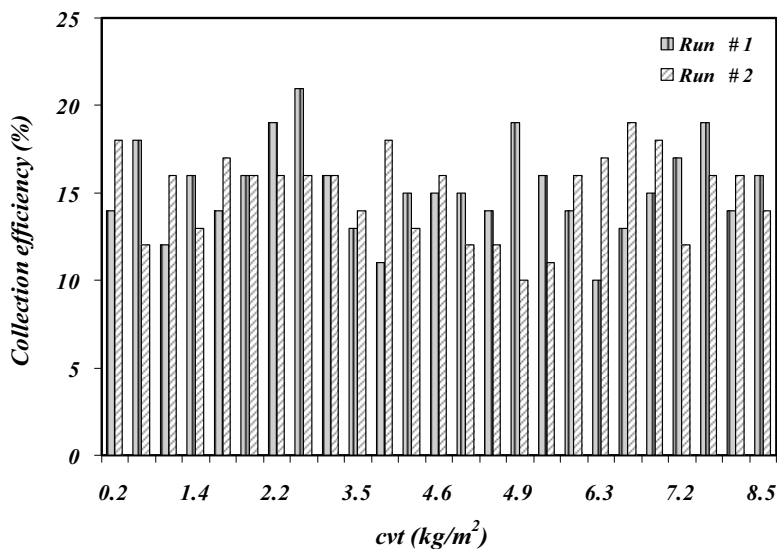


Fig. 8. Collection efficiency of an impaction wall device at dust-loaded condition.

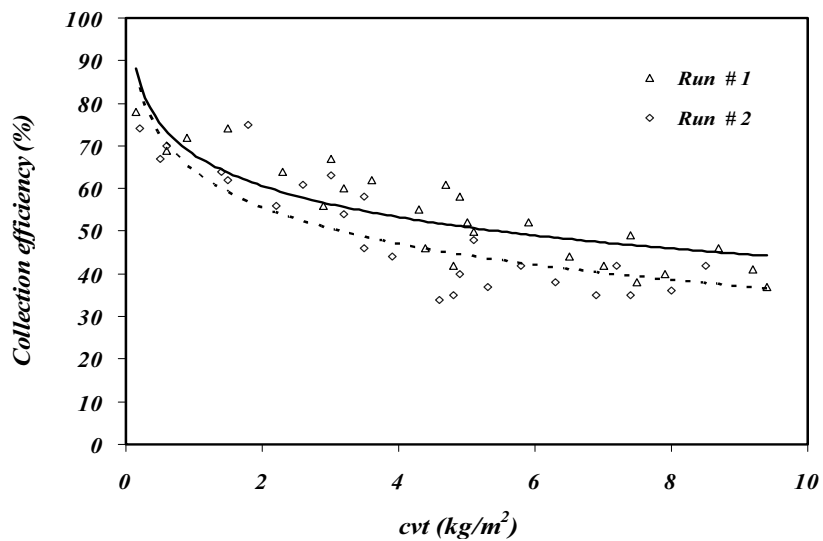


Fig. 9. Collection efficiency of the wire-plate ESP device at dust-loaded condition.

shelf life. Small particles were distributed in the rubber smoking chamber and perched on the rubber sheet surface, resulting in a color a little darker than normal. Parts of small particles were attached to the rubber-sheet surface, as well as the walls of the smoking chamber. And finally, the escaping soot particles will probably flow and spread to the environment.

The Color of the Dried Rubber Sheets

The results for the color of the dried rubber sheets come from comparing the period of exposure of rubber sheets to air prior to the drying process exposure time, the type of the rubber latex produced. And moisture content of the fuel wood used. Kalasee (2005); Tekasakul *et al.* (2005) and Tekasakul *et al.* (2006) used the Lovibond standard in which the color index of rubber sheets is not standard and a lower number indicates a lighter color of the sheets. In this standard, the results show that the rubber sheet obtained from drying in the smoking chamber, using soot particle separation equipment has the lightest color, with an index of 6.0-12.0. In the first to third experiments, the rubber sheets produced were 6.0 in the color index. The fourth to tenth experiments had color indexes of 8.0, and for the eleventh and twelfth experiments, the rubber sheets were 12.0. These results are better than the rubber sheet color under normal operation without separation equipment (with a color index as high as 16 or greater and a dark brown color from excessive deposition of soot particles on the rubber sheet surface, especially during the first day when the rubber sheets were still wet).

CONCLUSION

Soot particle separation using an impaction wall and ESP is suitable for operating in rubber smoking chambers. An impaction wall can collect large soot particles from 3.3-4.7 microns before entering the modified ESP. The results of building an impaction wall between the furnace and ESP causes the pressure, temperature, and velocity of hot gas in a rubber smoking chamber to drop. Therefore, controlling the combustion rate by an adjustable steel door on the front of the furnace should be considered for the improving the quality of cured rubber sheets. Improved soot particle collection for rubber smoking by an impaction wall and modified ESP could improve the shelf life of ESP more than 12-fold when compared with former ESP designs. The color of the dried rubber sheets with soot particle separation is better than without. The decreasing of soot particles from a rubber wood combustion system is an advantage for the environment, worker health and rubber sheet quality. Results of this study suggest a complete cleanup of hot gas before escaping to the environment. To save the earth by using ventilating windows on the rear wall and ceiling designed for separating the escaping soot particles from an impaction wall, the ESP, the walls in smoking chamber, and the rubber sheets. Designing the ventilating window must be considered due to the effects of temperature, pressure, and velocity of the hot gas flow in the chamber on energy consumption and the quality of the dried rubber sheets.

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