Removal of Soot Particles in Rubber Smoking Chamber by Electrostatic Precipitator to Improve Rubber Sheet Color

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Abstract

Soot particles from wood combustion in the rubber-sheet smoking process darkens the dried sheets, affecting their market price unfavorably. A technique to remove a portion of these particles, especially during the first day of drying, was investigated. A wire-cylinder type corona discharge device or electrostatic precipitator (ESP) was employed to remove the soot particles. Results from a laboratory collection performance test using polystyrene latex particles indicated that the ESP was suitable for use at 220 VAC, which is the highest available voltage supply. The field-test results in a model burner indicated that the device could be used for a period of about 10 hours without cleaning and it could still maintain the collection efficiency at a satisfactory level (higher than 40%). The color of the dried rubber sheets obtained from the smoking chamber in which the collecting device was installed was much lighter than that of the rubber sheets dried in normal operation without removing soot particles. This device could be used in a real rubber smoking chamber by installing 12 identical ESP units in the gas inlet to the chamber.

Keywords: corona discharge, rubber sheet, particle collection, wire-cylinder, high voltage

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Thailand leads the world in natural rubber production and export. Total production in 2004 was 2.9 million metric tons (Thailand Rubber Research Institute, 2005). About 43% was in the form of ribbed smoked sheets (RSS), in which the rubber latex is coagulated, squeezed to form thin sheets, and then dried in a smoking chamber. Energy consumption and quality of the dried sheets are two major concerns in the process. The color of the dried sheet affects the market price considerably because the RSS is graded according to the impurities in the sheet, as well as to the color. Rubber sheets that are exposed to excessive smoke from wood combustion are dark in color and, hence, the value can be downgraded. Currently, manufacturers deal with this problem by discharging a part of the dust-laden gas after combustion to the atmosphere without using it. However, this results in a huge loss of energy. In order to improve the color of the rubber sheets and not to waste energy, a means of reducing soot particles in the gas is needed. The gas does not require a complete cleanup, since soot particles contain phenolic compounds (Simoneit *et al.*, 1993) which hinder the formation of moulds and bacteria, thus preserving shelf life of the rubber sheets. In this study, an appropriate soot-collecting device is designed and tested in both the laboratory and the field.

RUBBER SMOKING CHAMBER AND PARTICLE CHARACTERISTICS

Most of the RSS manufacturers in Thailand reside in the south, where production is shifting from large-scale industries to community-level rubber cooperatives. About 500 cooperatives are currently operating throughout the country, each with a capacity to produce about 500-1,000 metric tons per year of ribbed smoked sheets (RSS). Rubberwood burning is the main source of heat, which is introduced into a burner's smoking chamber via 12 4-inch-diameter tubes located at the floor of the chamber (Fig. 1). Initially, when the wood is burned, the hot gas is clouded with dark soot particles, particularly when fresh wood is introduced to the burner. After the gas transfers heat to the rubber sheets, it is vented by natural convection through the ventilating lids located on the ceiling. This vented gas is moisture-laden during the first day of drying when the rubber sheets are quite wet. When the rubber sheets are exposed to excessive amounts of soot particles, they develop a dark and unfavorable color which in turn affects the price. Some of the soot particles need to be removed to lessen this problem especially during the first day of drying when the soot particles stick easily to the wetter surface.

Characteristics of the soot particles, particularly size and concentration, must be known to design an effective collecting device. Size distribution and mass concentration of soot particles from rubberwood combustion have been investigated in a previous work (Kalasee *et al*., 2003). The size distribution characteristics obtained by an Andersen sampler indicated a single mode of aerosol particles. Average mass median aerodynamic diameter (MMAD) was found to be 0.95 microns while the average value of geometric mean standard deviation (GSD) was 2.51. The mass concentration of the smoke particles was found to depend strongly on the moisture content of the fuel wood. In our study, it ranged from 47 to 1,358 mg/m^3 for a fuel wood moisture content of 34.5 to 107.5% dry basis. Here, the dry-basis moisture content is defined as the ratio of the water content present in the wood to the wood dry mass.

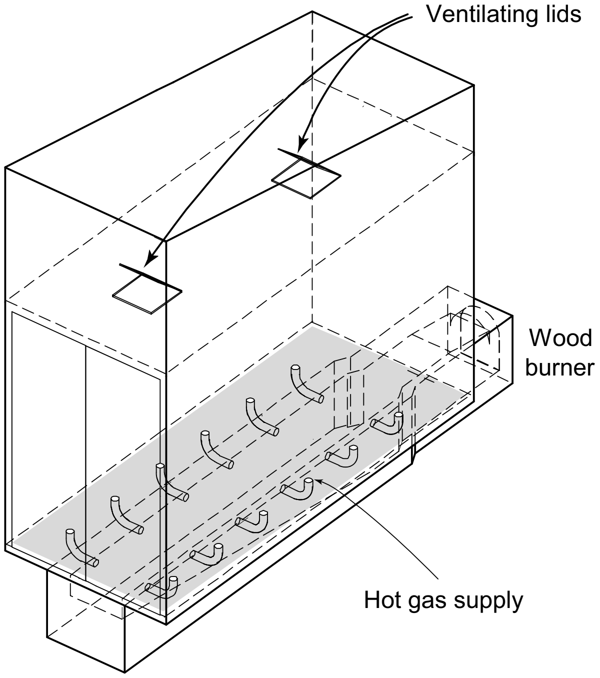


Figure 1. Schematic diagram of the rubber smoking chamber.

ELECTROSTATIC PRECIPITATOR

Because the soot particles are in the submicron range and the concentration is variable, one of the most effective technologies for the collecting device is to make use of a corona discharge device or an electrostatic precipitator (ESP). Particle collection by this technique has the advantage of a high collection efficiency (especially for small particles) and its pressure drop is low. Numerous attempts have been made in several applications to experimentally use this method to collect aerosol particles (Zukeran *et al*., 1997; Kim and Lee, 1999; Jedrusik *et al*., 2001; Laskin and Cowin, 2002; Jedrusik *et al*., 2003). Moreover, several modeling methods of collection performance have been developed to improve current theoretical works (Kim *et al*., 2001; Elayyan *et al*., 2002; Xiangrong *et al*., 2002). Chang *et al*. (1998) have studied the effects of dust loading on a wire-plate type electrostatic precipitator and its collection performance. They showed that the collection efficiency decreased as more dust accumulated on the collecting surface, but increased with applied voltage up to 10 kV. In order to enhance the collection efficiency for ultrafine particles, Kulkarni *et al.* (2002) showed that the use of a soft X-ray combined with a corona discharge is highly effective for increasing the charged fraction of particles and therefore enhancing the collection efficiency of an ESP. However, this technique is not suitable for use in the RSS manufacturing as it is too complicated for low-skilled workers to operate.

In this work, simple and low-cost ESP is used for the collection of soot particles. The installation of the collecting device immediately after the wood burner is not possible since the temperature of the gas is extremely high and modification of the burner would be needed. This would result in an increased capital cost and would not be affordable by small-scale RSS manufacturers. The best possible choice for installing the collecting device is where the gas enters the smoking chamber through the 12 4-inch-diameter tubes at floor level. These tubes are about 30-40 cm deep. A wire-cylinder-type corona discharge electrostatic precipitator has been designed to fit these tubes. The collecting electrode, made from stainless steel tube, is 7.6 cm in diameter and 25 cm long. A 0.3-mm-diameter copper wire is used as a corona-discharge electrode. The wire is held in the center of the device and separated from the collecting electrode by two ceramic holder tubes fixed to both ends of the collecting electrode as shown in Fig. 2. The collecting device is connected to a simple electrical circuit that supplies a high potential difference between the electrodes. The inlet voltage of 220 VAC is made adjustable between 0-220 V by a slide regulator (Chuan Hsin, SRV-10). This voltage is then transformed into high voltage (0-15 kV) by a neon transformer (LECIP, EX230A15N). A Wheatstone bridge circuit consisting of four high-voltage diodes (12 kV) is used to transform the high-voltage AC current to a rippled DC current with the maximum peak voltage of about 11 kV. In this work, the corona discharge wire is located at the negative electrode while the collecting electrode carries a positive charge. This simple circuit is used because it is easy to construct and is affordable for the manufacturers.

The relationship between the input and output voltages was measured by the use of a high-voltage probe (Textronix, P6015A) and an oscilloscope (Hitachi, V-252). The output voltage exhibits a linear correlation with the corresponding input voltage; the maximum output being 11 kV peak for the input of 220 V. The discharge current of a clean ESP, as shown in Fig. 3, is highly sensitive to the input voltage. The onset of corona discharge is at about 180 V. In this study, the maximum input voltage of 220 V corresponding to the output peak of 11 kV was used to ascertain that the corona discharge was sufficiently strong and stable for charging and collecting the particles. The influence of dust load on the discharge current is also shown in the graph and will be explained later in the “Results and Discussion” section of this paper.

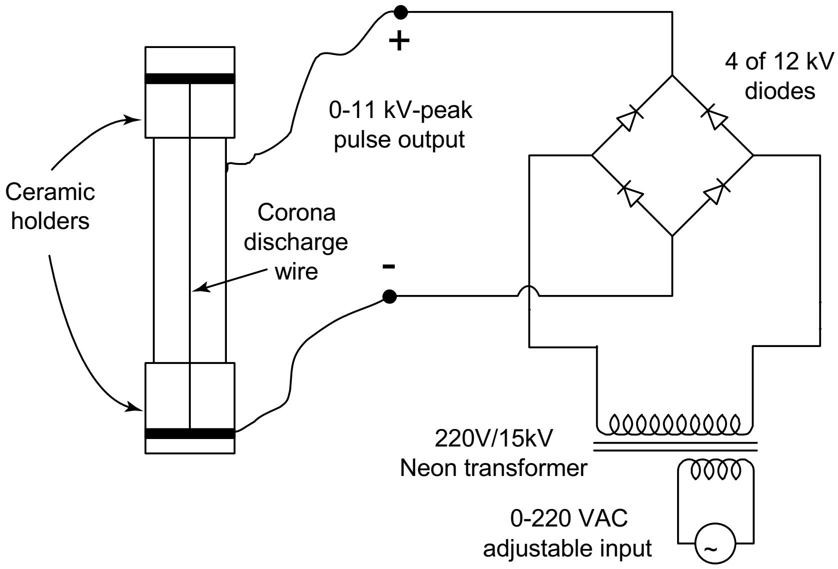


Figure 2. Diagram of the corona discharge device and electric circuit.

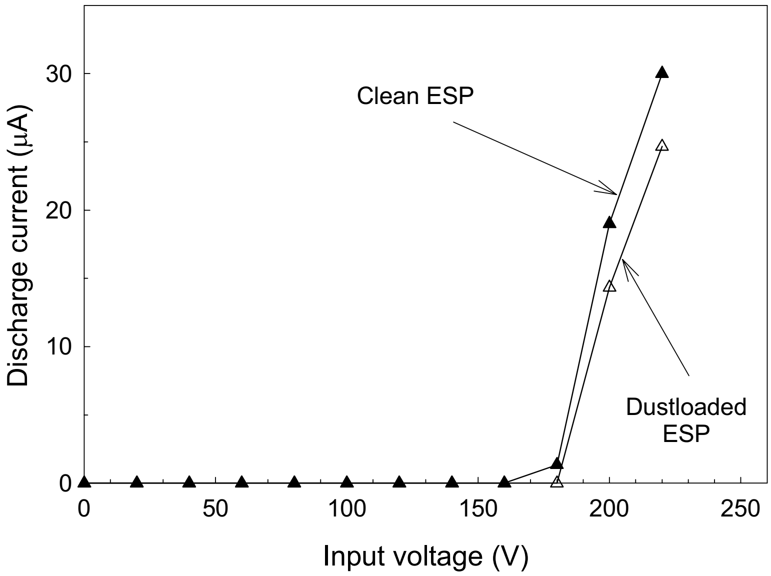


Figure 3. Discharge current characteristics of the clean and dust-loaded device.

EXPERIMENTAL WORK

The experiment was divided into three parts. In the first part, basic collection performance of the device was tested in the laboratory. In the second part, field-test performance in a model burner was evaluated. Finally, the designed ESP was installed in an actual rubber-smoking chamber for the evaluation.

Laboratory experiment to determine basic collection performance

In this experiment, the collection efficiency and pressure drop were measured. Spherical monodisperse polystyrene latex (PSL) (Duke Scientific) particles (sizes 0.5 and 1.0 micron) were used as test aerosol particles, because these are close to the MMAD of the soot particles known to occur in the smoking of RSS. Setup of this experiment is shown in Fig. 4. Droplets containing PSL particles were generated by an atomizer (Topas, ATM 225) and dried by the diffusion dryer. The PSL aerosol particles were neutralized by Am-241 and diluted with dry clean air. The aerosol was then introduced to the ESP. Flow rate was controlled by a vacuum pump (Gast, 0211-Y45F-G230CX), a needle valve, and an orifice meter. Pressure drop was recorded by a differential pressure transducer (MKS, Baratron Type 223). Collection efficiency was measured by sampling aerosol concentration at the inlet and exit of the collecting device using a laser particle counter (LPC) (Royco, Portable 330B). This LPC consists of five channels to cover the range of particle sizes; 0.3, 0.5, 1.0, 3.0 and 5.0 micron. The input voltage was adjusted to 100, 140, 180 and 220 V and the velocity was varied from about one to 15 cm/s. The collection efficiency was then calculated from

$$E_{\exp} = 1 - \frac{C_{exit}}{C_{inlet}} \quad (1)$$

where C_{exit} and C_{inlet} are particle number concentration at the exit and inlet of the collecting device.

The experimental results was compared with the collection efficiency calculated from the Deutsch-Anderson equation (Hinds, 1999)

$$E_{calc} = 1 - \exp(-V_{TE} A_C / Q) \quad (2)$$

where A_C is the collection surface area, Q is the flow rate, and V_{TE} is the terminal electric velocity. Detail of the Deutsch-Anderson equation and notations is given in White (1963) and Hinds (1999).

Field Test

A field test is necessary to obtain the collection efficiency when the equipment is used in a real situation. Because testing in the rubber smoking chamber is too difficult and time consuming, a model of the burner was built for the test. The schematic diagram of the field test equipment is shown in Fig. 5. In this experiment, the collecting device was installed in a tube connected to the flue. The aerosol was pulled through the flue by a vacuum pump used in the preceding section. The flow rate was set constant at 20 lpm in order to simulate known condition in the RSS drying chamber. Collection efficiency was determined on a mass basis by collecting soot particles at the inlet and exit of the device on separate filters. The mass of the blank and used filters was measured by a 4-digit analytical balance (Mettler, AB204-S). The difference in the collected mass between the two filters defines the collection efficiency. The filters were collected every 30 minutes and new filters were replaced to give a representative collection efficiency for each time interval. The experiment was carried out over a total of 10 hours. Soot concentration was maintained at the same level by constantly supplying wood to the burner; however, it was impossible to maintain constant soot concentration due to the variable nature of the wood combustion process. The input operating voltage was kept constant at 220 V which corresponded to 11 kV of the output peak.

The ESP that collected the soot particles for 30 minutes was then brought for testing into the laboratory using PSL particles. This was to compare the collection efficiency of the device while it was in a dust-loaded condition with the same device when it was clean.

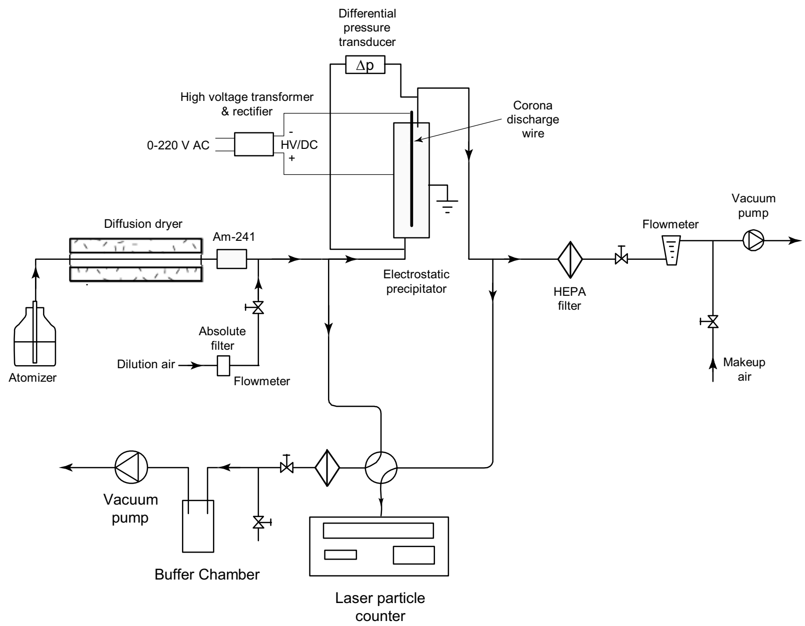


Figure 4. Laboratory setup for collection performance test of the electrostatic precipitator.

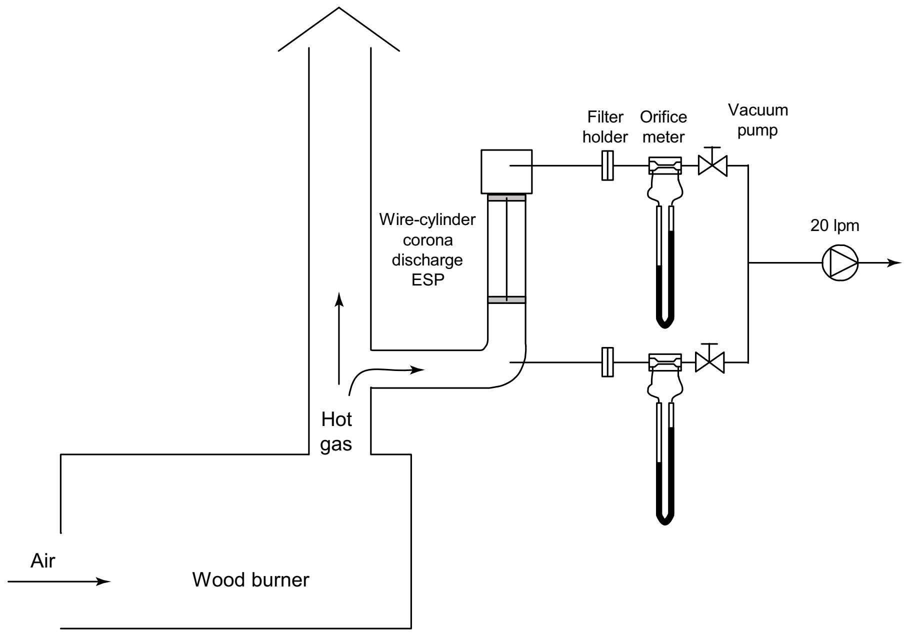


Figure 5. Schematic diagram of the field test setup.

Rubber smoking

Twelve identical ESPs have been built and installed in the rubber smoking chamber of a commercial RSS drying unit. All of them were connected to the same high-voltage circuit. The operating voltage was 220 VAC for the input as in the previous case. The total drying time for the rubber was about four days, but the ESP was operated only within 30 minutes of the introduction of fresh wood to the burner since the smoke is at its greatest density in this period. After 30 minutes of each fresh wood addition, the soot concentration is known to be low and the effect on the color of the rubber resulting from soot deposition on the surface is correspondingly small. Accordingly, the ESP circuit was turned off. The total operating time for the ESP was 10 hours.

RESULTS AND DISCUSSION

Experimental results in the laboratory are shown in Figs. 6 and 7 for the aerosol particle sizes of 0.5 and 1.0 micron, respectively. The results indicate the initial collection performance because the ESP is cleaned on a regular basis. The collection efficiency is shown as a function of velocity for the input voltages from 100 - 220 V. The results are plotted against the theoretical values obtained from the Deutsch-Anderson equation. It can be seen that the collection efficiency decreases as the velocity increases, and the results agree very well with the values obtained from the Deutsch-Anderson equation for the highest input voltage of 220 V when the corona discharge is well-established. The results at 180

V are, however, below the theoretical values for the case of 0.5 micron particles, but the agreement for 1.0 micron particles is quite good. This may be because conditions are close to the onset of the corona discharge, as described in Fig. 3. A slight difference in input voltage adjustment may be responsible for the difference. Theoretical values for lower voltages were not calculated or presented because the discharge current was too small for accurate readings to be taken. Overall, agreement between experimental data and theoretical predictions from the Deutsch-Anderson equation is good. The best operating voltage for this collecting device is, therefore, that of its highest input voltage of 220 V which is equivalent to output potential of 11 kV.

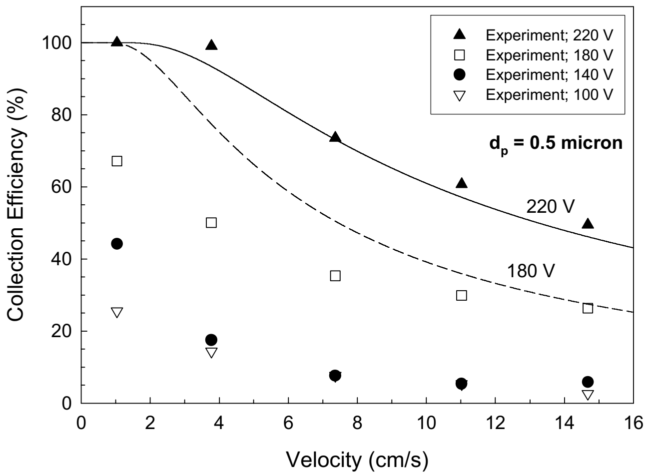


Figure 6. Collection efficiency of the ESP as a function of velocity for 0.5-micron particles for various input voltages. The lines are plots of the Deutsch-Anderson equation of indicated voltage.

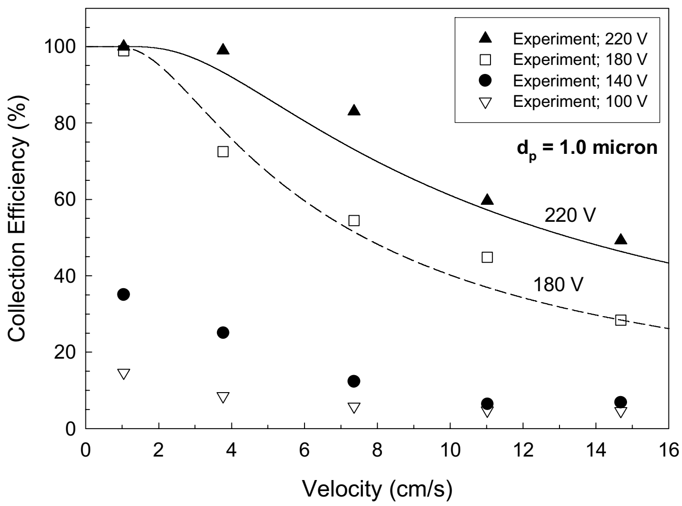


Figure 7. Collection efficiency of the ESP as a function of velocity for 1.0-micron particles for various input voltages. The lines are plots of the Deutsch-Anderson equation of indicated voltage.

The pressure drop measured by the transducer was undetectably low. This is advantageous because it means that the energy loss caused by the introduction of the device is minimal thus allowing natural convection to move the flue gases through the collecting device.

Results obtained from the field test operated under dust loading condition are shown in Fig. 8. In this case, the input voltage was set to the highest value of 220 V. In this graph, the collection efficiency is plotted against the dust-loading parameter (cvt); where c is the particle mass concentration, v is the aerosol velocity in the collecting device, and t is the collection time. The collection efficiency is shown to decrease as the dust loading is increased. Thus, during 10 hours of operation in the test burner, the discharge current decreases due to particle deposition on the surface, as shown in Fig. 3. It is also found that the onset of corona discharge is slightly retarded by high dust loading. The discharge current of the dust-laden ESP produced by the maximum input voltage of 220 V is about 17% below that measured on the clean ESP. This reduction of the discharge current therefore causes the reduction of the collection efficiency. The result of the testing in the laboratory is plotted as a black circular dot in the same graph in Fig. 8. These results agree quite well with the results obtained in the field test.

Photographs of the ESP used in this experiment are shown in Fig. 9. Figure 9 (a) shows the new ESP while Fig. 9 (b) shows the ESP that has been used for 10 hours. Twelve identical ESP units were installed and operated for a total of 10 hours over each 30-minute period after adding fresh fuel wood. The used device was found to be loaded with soot particles and tar from wood combustion. It therefore required cleaning before reuse to maintain the collection efficiency at the highest level attainable. Due to the limitation of the space between the collecting device and the rubber sheet holder cart, no cleaning mechanism was fitted during these experiments. To fit such a device, the holder cart will need to be suitably elevated.

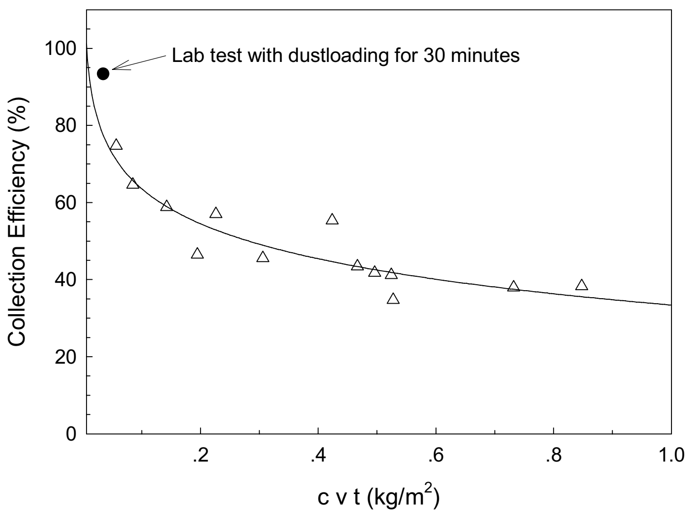


Figure 8. Collection efficiency of the ESP device at dust-loaded condition.

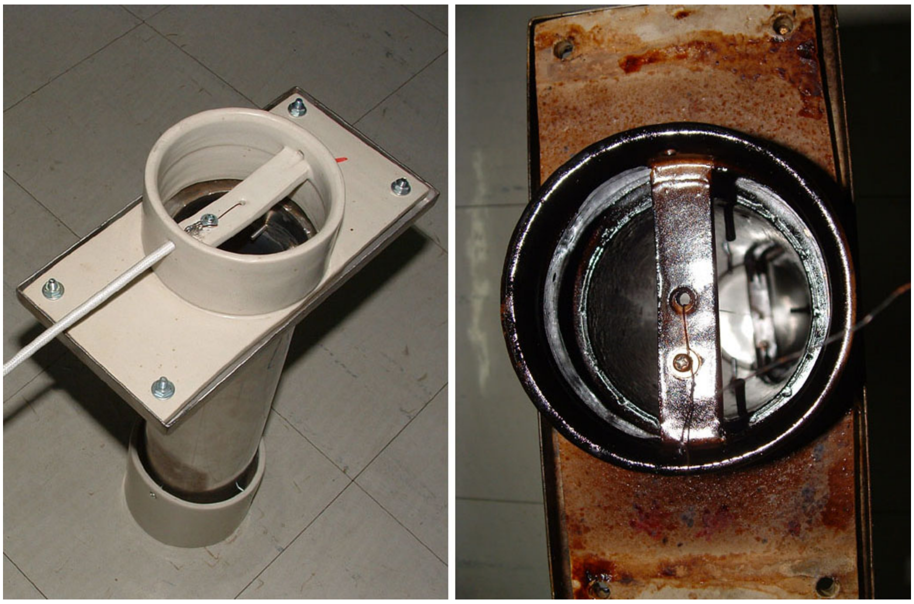
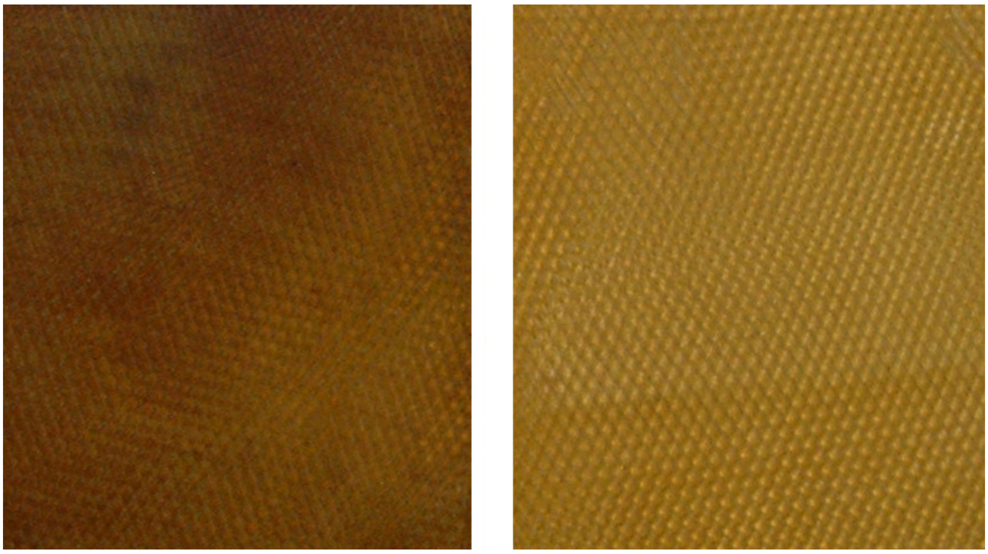


Figure 9. Collecting device: (a) new, and (b) after 10-hour use.

The results for the color of the rubber sheets are shown in Table 1 and Fig. 10. Values in Table 1 are the color index obtained from comparison with the Lovibond standard used for block rubber measurement because there is no standard for color indication of rubber sheets. The measurements were carried out at the Songkhla Rubber Research Institute laboratory. The lower number indicates lighter color of the rubber sheets. The rubber sheet obtained from drying in a smoke-free Liquefied Petroleum Gas (LPG)–equipped dryer has the lightest color with the index of 5.0. Under normal operation without installing the ESP, the rubber sheet may have the color index as high as 16 or greater. The color is dark brown, as shown in Fig. 10(a), due to excessive deposition of soot particles on the rubber sheet surface, especially during the first day when the rubber sheets were still wet. The color index of the rubber sheet obtained from the room in which the collecting device was installed is 8.0. The color is light brown, as shown in Fig. 10(b), and the difference is visually obvious. It is important to note that color of the dried sheets also depends on other factors; i.e., period of the rubber sheet exposed to air prior to the drying process, type of the rubber latex, and moisture content of the fuel wood used. However, in this work, the influence of these factors was minimized by controlling the conditions. The difference in the color is therefore attributable to the concentration of the soot particles.

Table 1. Color indices of rubber sheets dried under various conditions.

Rubber sheet drying condition	Color Index
LPG dryer	5.0
Smoke chamber; ESP not installed	10.0 to >16.0
Smoke chamber; ESP installed	8.0



(a) (b)

Figure 10. Comparison of the rubber sheets dried in (a) a room without collecting device, and (b) in a room equipped with the collecting device.

CONCLUSION

The electrostatic precipitator utilizing a corona discharge presented in this work is suitable for operating in rubber smoking chambers. Collection performance, when tested under laboratory conditions agrees with the Deutsch-Anderson equation. When tested in the field, the collection performance decreases according to the quantity of collected particles on the surface which directly accounts for the observed reduction in the corona discharge current. However, reduction of the efficiency does not significantly affect the operation because it is not necessary to attain high collection efficiencies for rubber smoking. Partial exposure of the rubber sheets to the smoke is still useful in preservation from molds and bacteria. Results from drying rubber sheets in a real smoking chamber show that the color of the rubber sheets dried using the soot collecting device is improved significantly. One concern is that the cleaning process of the device when loaded with soot particles needs to be developed. In this work, no cleaning process was used during operation and this resulted in the heavy deposition of soot and tar. Although the result is satisfactory, the addition of a cleaning device when operating the ESP would be extremely useful because it should not require complete cleaning every time the rubber smoking process is finished. Recommendations for future work on the application of the device include the installation of a cleaning mechanism by either modifying the rubber sheet holder cart or by redesigning the burning chamber itself. In the latter case, the collection of the soot particles downstream of the burner may be facilitated by installation of a long duct outside of the chamber equipped with a single ESP.

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