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# Factors Affecting Rubber Sheet Curing

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**ABSTRACT**

*Factors affecting the curing of rubber sheets were studied. Experiments were carried out on 15 kg batches of rubber in an environmentally controlled chamber. Parameters selected for the study were relative humidity (RH) of inlet air, air flow rate and loading density (kg of rubber/m³ of chamber). Curing time was inversely proportional to the relative humidity of the inlet air. Air flow rate had minimal effect on the curing behaviour of the rubber sheets. A test with loading density similar to, and specific air flow rate slightly less than, the actual practice in factories, but inlet air of 40% RH, resulted in a curing time of 40% of that currently required in the factories. A full-scale experiment to investigate the effects of firewood moisture on rubber smoking time was undertaken by firing two smoking rooms with green wood (42.19% moisture) and dry wood (19.36% moisture). The room fired with dry firewood shortened the smoking time by about 1 day but consumed more pieces of firewood.*

## INTRODUCTION

After Malaysia, Thailand is the world's second biggest rubber producing country. It was estimated that during the 7th National Economic and Social Development Plan (1992-1996) the gross rubber production of the country (Thailand) will increase from $1.30 \times 10^6$ tons to $1.58 \times 10^6$ tons. About 80% of the country's rubber product is ribbed smoked sheet (RSS) rubber which makes Thailand the biggest RSS producing and exporting country in the world [1].

Ribbed unsmoked rubber sheets are produced in rubber plantations by smallholders. The surfaces of the sheet have criss-cross rib markings (hence the term "ribbed"). The rubber smoking factories procure raw materials through contracted dealers to produce the ribbed smoked sheets (RSS). The smoking process occurs in a smoke house using firewood as the source of heat and smoke. The smoke house is simply a series of 4.5 x 8 x 16 $m^3$ rooms constructed from brick and mortar. Wood furnaces are attached to the back walls of the rooms. Hot gas and smoke are conveyed through an underground tunnel into the room to dry and cure the rubber and then exhausted through ventilation ports on the ceiling. Basically, the functions of the smoke house are to dry the rubber sheets, to enable the sheets to absorb creosotic and other antiseptic substances that have a preservative effect on the rubber and to impart a uniform colour to the smoked sheets. The antiseptic substances in the smoke are believed to prevent the development of moulds and other microorganisms in the sheets. Reducing moisture content of rubber sheets to 0.3-0.4% wet basis by exposing them to a temperature of about 70°C results in transparent sheets which are often referred as cured rubber sheets.

A survey of rubber smoking factories in Southern Thailand revealed that the rubber smoking industry consumed 0.25 $m^3$ of firewood per ton of the smoked rubber [2]. Consequently, it can be estimated that about 202 x $10^3$ $m^3$ of firewood is being consumed annually by the rubber industry. However, the rubber industry as a whole is a net energy producer, i.e., surplus wood is available from the replanting after the economic life time of the rubber trees [2]. More importantly, a monitoring of the smoking process found that energy (from the firewood) was not a vital factor for the industry as it accounted for only 1-2% of the production cost [3].

Generally, the per-batch smoking time of 45 tons of rubber is in the range of 5-9 days depending on the season (dry or wet) which ultimately reflects the adverse effect of moisture in the atmosphere. Monitoring of the rubber smoking process [3] revealed that, for a batch of smoking, water vapor in the combustion air admitted into the smoking room was calculated as 2 tons and 5 tons during the dry and wet seasons, respectively, while the moisture removed from the rubber was approximately 1.2 tons. Moreover, about 1 ton of water was emitted from the moisture of the firewood. Consequently, it was envisaged that the smoking time could possibly be reduced to increase the productivity by the dehumidification of the combustion air [3,4]. However, the curing behaviour of rubber sheets with respect to the humidity surrounding them is still quantitatively unclear. In general, decreasing the relative humidity will result in a shorter drying (or curing) time. This article reports results of studies on the effects of the humidity as well as other factors such as air flow rate and loading density (kg of rubber/$m^3$ of room) at laboratory scale. Results of smoking the rubber with dry and green firewood in two full-scale smoking rooms are also presented.

## MATERIALS AND METHODS

An environmentally controlled chamber, shown schematically in Fig. 1, was designed and constructed from angle steel bars and gypsum boards. The chamber has a volume of 0.6 x 1.8 x 1.8 $m^3$. An air compressor was used to supply relatively dry air to the chamber. Humidity of the inlet air was adjusted to a desired level by a proper mixing of two streams of air; the dry air from the compressor and saturated air. The saturated air was obtained by bubbling the air in a column of water. The humidity was determined by wet bulb and dry bulb temperatures. Air flow rate was controlled and measured by an air flow meter (Dwyer Rate-Master RMA-23, USA). The inlet air passed through a set of electrical heating elements which were hung vertically in an insulated steel pipe. The temperature inside the chamber was controlled at 65°C by a temperature controller (Super SP-2 temperature controller, S. Pairach Supply Co., Thailand). Rubber sheets were graded by an experienced person so that consistent thickness and moisture content of every sheet were attained. The nominal size of a sheet was 100 x 50 $cm^2$ and 3-4 mm thick. The average weight was 1.16 kg/sheet. Rubber sheets were washed before being placed on aluminum rods, which were subsequently tied to a strain gauge type load cell (Transtronic FAD-10, Taiwan and MM-4051 signal transmitter, Wilkerson Instrument Co., USA). Temperatures at various points in the chamber, as depicted in Fig. 1, were read by K type thermocouples and a digital thermometer (Omega HH81 digital thermometer, Omega Engineering, USA). There were 9 experiments in this study programme as described in Table 1.

In actual practice, where the capacity of the room is about 40-45 tons of rubber, the specific air flow rate was quoted at 0.02 $m^3$/h for a kilogram of rubber [5]. To determine the effects of the inlet air humidity, the air flow rate for experiments 1-5 was set to the actual figure (0.02 $m^3$/h kg or 0.3 $m^3$/h) but the inlet air relative humidities were varied from 80% to 20%. Likewise, the

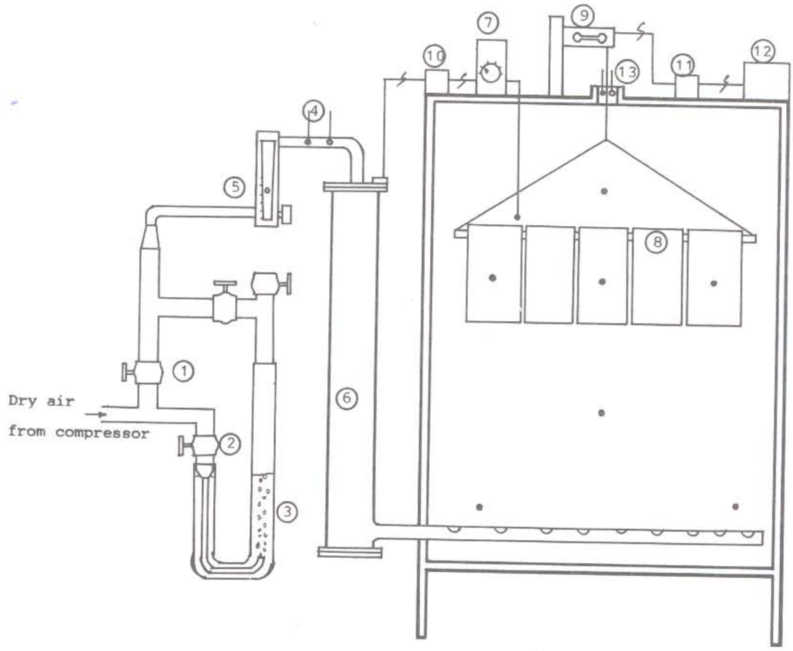


Fig. 1. Environmentally controlled chamber. (• Thermocouple)

1. Dry air valve
2. Saturated air valve
3. Water column (clear plastic tube)
4. Wet bulb and dry bulb temperature of inlet air
5. Air flow meter
6. Insulated pipe with heater
7. Temperature controller
8. Rubber sheets on aluminium rod
9. Load cell
10. Magnetic contactor
11. Signal transmitter
12. Load display
13. Wet bulb and dry bulb temperature of exhaust

**Table 1. Details of experiments.**

| Experiment | Inlet Air RH (%) | Air Flow Rate (m³/h) | Initial Mass of Wet Rubber (kg) |
|---|---|---|---|
| 1 | 80 | 0.3 | 15.620 |
| 2 | 60 | 0.3 | 15.385 |
| 3 | 40 | 0.3 | 16.285 |
| 4 | 20 | 0.3 | 14.975 |
| 5 | 20 | 0.3 | 15.340 |
| 6 | 40 | 0.18 | 15.742 |
| 7 | 40 | 0.6 | 15.455 |
| 8 | 40 | 1.2 | 15.651 |
| 9 | 40 | 2.01 | 123.900 |

effects of the inlet air flow rate were determined from experiments 6-8, where the relative humidity was fixed at 40% (the predetermined and expected appropriate value), by varying the air flow rates from 0.18 $m^3/h$ to 1.2 $m^3/h$ (specific flow rate 0.012-0.08 $m^3/h$ kg). The last experiment was conducted at 40% relative humidity and specific air flow rate of 0.016 $m^3/h$ kg but the loading density was identical to the actual practice (67.73 $kg/m^3$) which required about 124 kg of rubber sheets. In this experiment the whole unit was placed on a 500 kg capacity scale (Berkel, Rotterdam-Holland, resolution 250 g) to monitor the weight loss instead of using the low capacity electronic load cell. Data were acquired every 30 minutes. The end of the drying process, which was judged by an experienced worker from a rubber factory, was indicated by the completely clear appearance of every sheet.

Previous study [3] showed that green firewood contributed about 24% of water to the smoking process which is undesirable for drying the matter. The effect of water contained in the firewood was investigated by smoking the rubber in two rooms simultaneously (in order to achieve identical ambient conditions) but using green firewood in one room and dry firewood in the other. Green and dry firewood were sorted according to their appearance, storage history (the pieces at the bottom of the stock pile are usually the dry ones). Every piece of firewood was weighed and cut in the middle to give a piece of about 1 cm in thickness. The pieces were weighed and dried in an oven at 70°C until constant weight was obtained. Moisture content of every piece of firewood was subsequently calculated. Rubber sheets in the smoking rooms were regulary observed to prevent unnecessarily prolonged smoking and hence obtain the correct smoking time. The two smoking rooms in this experiment were rooms number 3 (green wood) and 4 (dry wood). The firing started at 4 pm.

## RESULTS AND DISCUSSION

The experimental results are presented quantitatively in Table 2. In general, the moisture removed from the rubber was less than 5% of its initial weight.

### Effects of Inlet Air Moisture

Experiments 1-4 gave the effects of the inlet air moisture on the curing characteristic of the rubber sheets. The inlet air relative humidities under the study were 80%, 60%, 40% and 20% at room temperature 30-32°C. The corresponding figures for the test cell temperature (65°C) were 15%, 11%, 7% and 3.5%, respectively. Figure 2 shows the curing characteristic of the rubber sheets at various relative humidities of the inlet air. It is obvious that the lower relative humidity results in a shorter curing time. A high drying rate at the beginning, due to vaporization of the wetted surface, was apparent for every experiment. When the surfaces of the sheets were still relatively wet, the sheets were at the wet bulb temperature of the surrounding air. The rate of evaporation was controlled by the rate at which heat could be transferred to the sheets to provide latent heat of evaporation of the water. Heat transfer and therefore evaporation, depends on the temperature difference between the air and the sheets. In other words, the drying rate at this stage is proportional to the difference between the wet and dry bulb temperatures of the surrounding air.

Curing times for the experiments with 60%, 40% and 20% RH were 76.6%, 59.6% and about 50% of that for the 80% RH experiment, respectively. It is interesting to note that a high proportion of the steady-weight periods occurred in the high humidity surroundings, Fig. 2. The drying mechanism in the steady-weight period is diffusion [6], which is influenced by the humidity of the

**Table 2. Results of experiments.**

| Parameter | Expt. | Inlet Air RH (%) | Air Flow Rate ($m^3/h$) | Moisture Removed (%) | Curing Time (min) | Relative Curing Time (%) |
|---|---|---|---|---|---|---|
| | 1 | 80 | 0.30 | 3.65 | 4230 | 100 |
| Inlet air | 2 | 60 | 0.30 | 2.60 | 3240 | 76.6 |
| relative | 3 | 40 | 0.30 | 2.37 | 2520 | 59.6 |
| humidity* | 4 | 20 | 0.30 | 2.09 | 2040 | 48.2 |
| | 5 | 20 | 0.30 | 3.24 | 2160 | 51.1 |
| | 6 | 40 | 0.18 | 3.50 | 2760 | 100 |
| Air flow | 3 | 40 | 0.30 | 2.37 | 2520 | 91.3 |
| rate@ | 7 | 40 | 0.60 | 3.76 | 2640 | 95.6 |
| | 8 | 40 | 1.20 | 4.70 | 2460 | 89.1 |
| loading density** | 9 | 40 | 2.01 | 4.60 | 2700 | – |

* Average loading density = 7.98 $kg/m^3$, specific air flow rate = 0.02 $m^3/h$ kg.
@ Average loading density = 8.03 $kg/m^3$.
** Loading density = 63.73 $kg/m^3$ and specific air flow rate = 0.016$m^3/h$ kg.

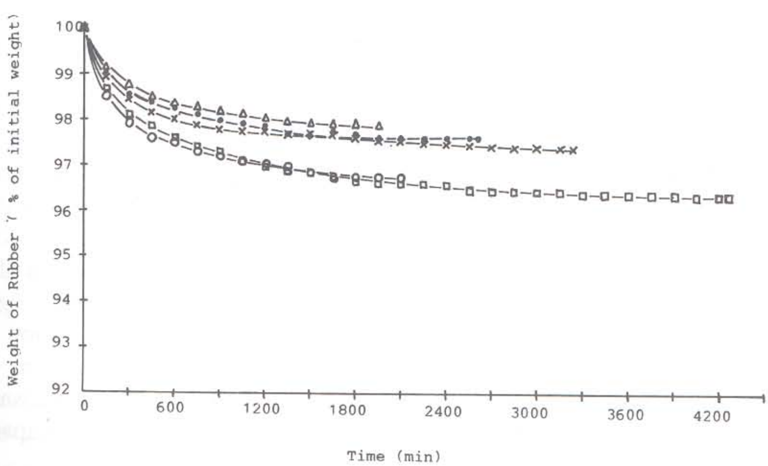


Fig. 2. Effects of inlet air relative humidity on curing time.

□ 80% RH, curing time 4230 min, final weight 96.35% of initial weight
× 60% RH, curing time 3240 min, final weight 97.40% of initial weight
● 40% RH, curing time 2520 min, final weight 97.63% of initial weight
Δ 20% RH, curing time 2040 min, final weight 97.91% of initial weight
o 20% RH, curing time 2160 min, final weight 96.76% of initial weight

surroundings and the temperature. The humidity affects the equilibrium moisture content while the temperature affects the diffusion.

The curing process finished when the sheets were transparent. Since this occurs at a certain moisture content (0.3-0.4% wb), the higher moisture removed in Table 2 means higher initial moisture. Therefore, one might argue that the variation of the curing times in experiments 1-4 was just the result of the differences in initial moisture content of the rubber, because, accidentally, rubber with higher moisture was tested with air of higher humidity (see Table 2). Therefore, the experiment with 20% relative humidity was repeated (experiment 5) using rubber as moist as that of experiment 1. The result of experiment 5, which was included in Fig. 2, confirmed the advantageous effect of the low relative humidity of the inlet air.

Since the end of the experiment was determined by the completely clear appearance of every sheet, the inconsistent or non-uniform initial condition of the rubber sheets would inevitably affect the result. That is, the curing time of each experiment depends solely on the thickest and moistest sheet. However, the irregularity of the samples seemed insignificant as the curing time, Fig. 2, strongly depended on the inlet air moisture.

**Effects of Air Flow Rate**

Results from experiments 1-5 revealed that the lower the humidity of the inlet air used, the shorter was the curing time. However, the minimum relative humidity may not be economically practical. There was only 10% difference in curing time between the 40% RH and 20% RH experiments. The advantage of shorter curing time at 20% RH could possibly be overridden by the higher cost of acquiring such dry air. It is, therefore, at this stage, desirable to limit the inlet air relative humidity at 40%. The effects of air flow rate on the curing behaviour of the sheets were determined by keeping the relative humidity of the inlet air constant at 40% but varying the flow rate as shown in Table 2.

Surprisingly, the results, Fig. 3, showed that the air flow rate had little effect on the curing time. The experiments in this series had a maximum air flow rate 6.7 times that of the minimum flow rate but the difference in curing times was just less than 10%. The 10% discrepancy might be the hidden effect of the difference in initial moisture content of the rubber rather than the direct effect of the air flow rate. An attempt to shorten the smoking time by installing ventilation fans was made in some factories. However, it not only failed to serve the objective but also resulted in higher fuel consumption in order to maintain the required room temperature [7]. High air velocity works well for evaporation (when the rubber is still wet) but not for diffusion which is the mechanism responsible for removing the last few percentage points of moisture [8]. In actual practice, the inlet combustion air of about 700 $m^3/h$ was found to be unnecessarily high [3]. Therefore, if dry air is incorporated into the process, a lower (than 700 $m^3/h$) capacity air dehumidifier should be sufficiently effective.

**Curing with High Loading Density**

Loading density has a direct effect on hot air circulation inside the room. Although the previous experiments revealed that air flow rate, hence the circulation, had an unnoticeable effect on curing time, the final experiment (number 9) was carried out with a loading density equal to that presently used in the factories (63.73 $kg/m^3$). The air flow rate was 2.01 $m^3/h$ (specific air flow rate 0.016 $m^3/h$ kg). The drying characteristic of the high-loading-density experiment is shown in Fig. 4. It is obvious that the drying curve in Fig. 4 is different from the curves of the low-

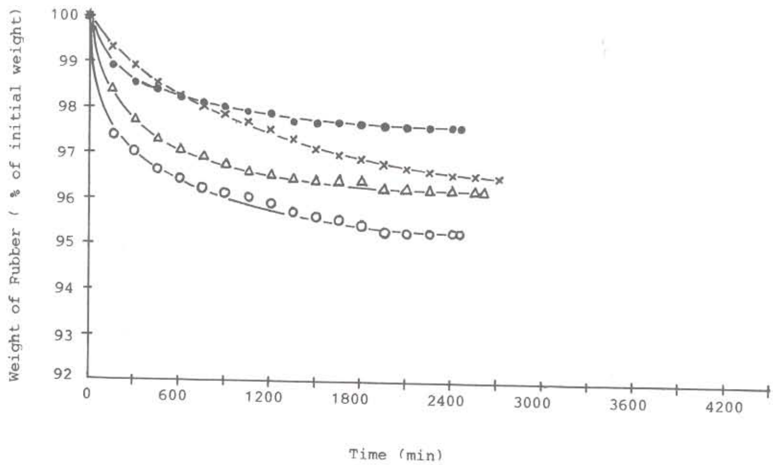


Fig. 3. Effects of air flow rate on curing time (40% RH).

× 0.18 $m^3$/h, curing time 2760 min, final weight 96.50% of initial weight
● 0.30 $m^3$/h, curing time 2520 min, final weight 97.63% of initial weight
△ 0.60 $m^3$/h, curing time 2640 min, final weight 96.24% of initial weight
o 1.20 $m^3$/h, curing time 2460 min, final weight 95.30% of initial weight

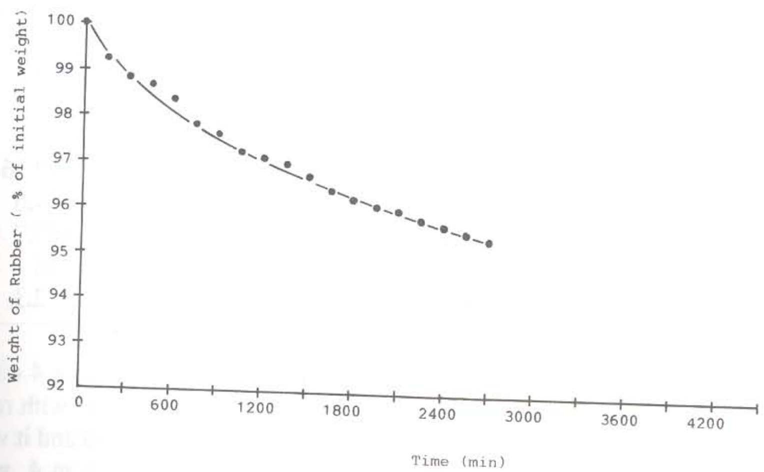


Fig. 4. Results of actual loading density (63.73 kg/$m^3$), 40% RH, specific air flow rate 0.016 $m^3$/h kg, drying time 2700 min, final weight 95.40% of initial weight.

loading-density experiments. Figure 4 has a lower drying rate at the beginning of the process compared with the low-loading-density results, probably because of limited circulation of air. Moreover, it exhibited no steady weight period at the end. The curing time was 2700 min which was in the same range as the low-loading-density experiments.

**Effects of Firewood Moisture**

A summary of the data on the firewood used is presented in Table 3. The initial moisture contents of the rubber in the two rooms were not determined in the experiment because there was insufficient data to perform a mass balance calculation. Assuming that the rubber in the two rooms had the same initial conditions, Table 3 implies that smoking time can be shortened by 19% if dry firewood is used. The furnace operator and the factory manager both agreed that the smoking with dry firewood in this experiment (room 4) finished about 1 day before the usual schedule. Although the mass of firewood used in the two rooms was different, apparently the two rooms consumed the same amount of "real dry wood". The real dry wood is the total mass of firewood subtracted by the mass of moisture. A greater amount of dry firewood, in terms of the number of pieces, was required compared to the green firewood because the dry firewood was burnt at a faster rate. This resulted in two undesirable consequences. Firstly, it caused a shorter furnace refill period (2.3 h v.s 3.3 h) and a higher number of refills (48 times v.s. 41 times) even though the processing time was shorter (110 h v.s. 135.5 h). Secondly, the fuel cost is higher since firewood is sold on by a volume basis. But the increase in fuel cost is insignificant as it contributes only 1-2% of the overall production cost [3].

**Table 3. Firewood used : green and dry conditions.**

| | Room | |
|---|---|---|
| | 3 (green) | 4 (dry) |
| Smoking time (h) | 135.5 | 110 |
| Firewood – total consumption (kg) | 3384.9 | 2405.3 |
| – number of wood (piece) | 419 | 580 |
| – average weight (kg/piece) | 8.1 | 4.1 |
| – average moisture (%) | 42.19 | 19.36 |
| – real dry wood (kg) | 1956.8 | 1939.6 |
| – water from wood (kg) | 1428.1 | 465.7 |
| – times of furnace refill | 41 | 48 |
| – average hour of refill (h) | 3.3 | 2.3 |

Figure 5 shows that the mass of firewood thrown into the furnace of room 4 was always less than that in room 3. The patterns of firewood consumption of the two rooms with respect to time were similar. Humidity ratios of the exhaust of the two rooms were measured and it was found that the exhaust of room 3 (green wood) was constantly wetter than that of room 4, which was the result of moisture in the green firewood (1428.1 kg compared to 465.7 kg for dry wood). It must be noted that at one point the temperature in room 4 was too high and the furnace operator had to dampen the fire.

## GENERAL DISCUSSION

For rapid curing, the rubber sheets should be as thin and porous as possible (to reduce the diffusion time), high temperature and low humidity should be used throughout and in the early stage high air velocity is advantageous (for rapid evaporation). An air speed of 0.5 m/s gave an

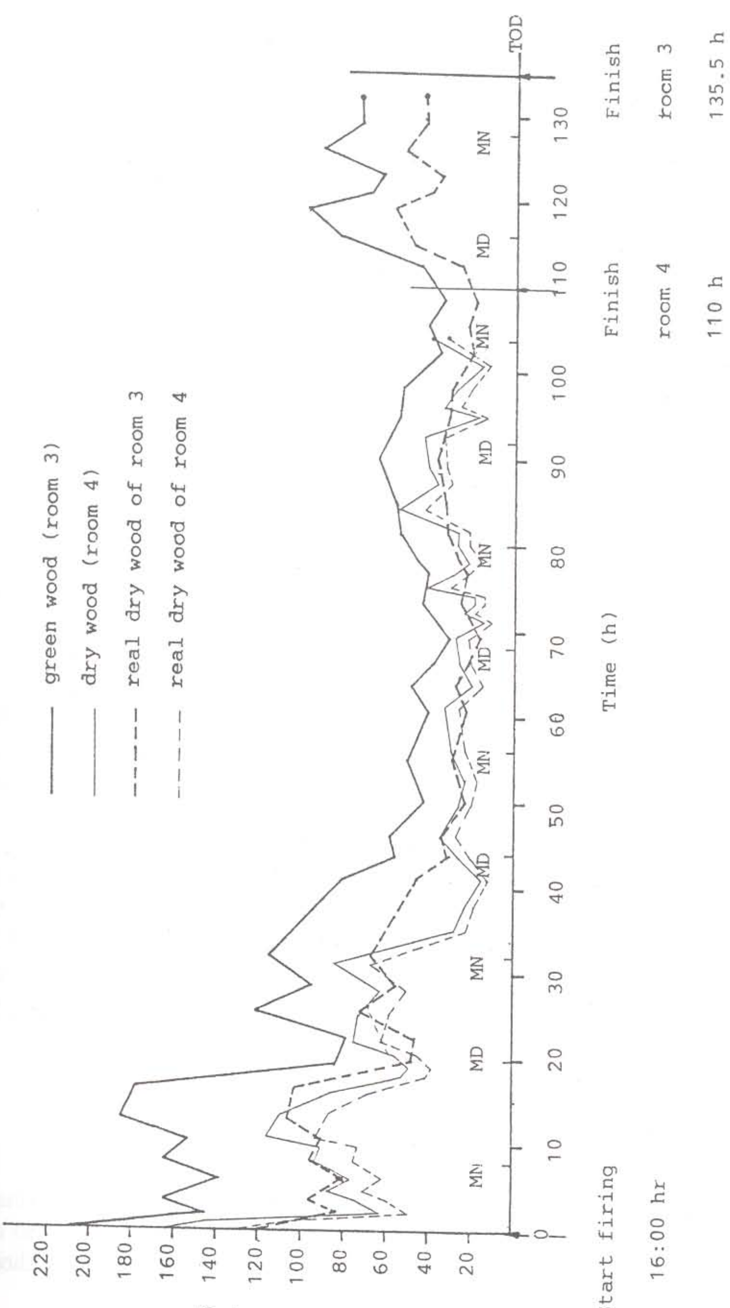


Fig 5. Firewood consumption of room #3 (green wood) and #4 (dry wood).
TOD = Time of Day, MD = Mid Day, MN = Mid Night

evaporation rate two to three times that obtained under natural convection conditions [9]. The air speed in this experiment was far below the figure quoted in the literature. There are practical limitations to the application of these conditions. If the sheets are machined too thin, the space required for the rubber and the labour needed for handling the sheets are all increased. Extreme high temperatures will damage the sheets by blistering. The high air velocity will increase fuel consumption.

Results from the experiments indicate that the use of dry air should greatly affect the rubber industry in terms of increasing the productivity and decreasing the production cost (firewood). Assuming that the ambient relative humidities of the wet and dry seasons are 80% and 70%, respectively, the corresponding amounts of water that have to be extracted from the 700 $m^3/h$ air flow rate (into the furnace) are 9.6 kg/h and 4.9 kg/h in order to obtain 40% relative humidity at 32°C. The creation of an economically viable dehumidifier that possesses such a capability is considered the ultimate goal of this project. Research on and development of such a dehumidifier for a field trial is currently underway at the Department of Mechanical Engineering, Prince of Songkla University. However, it must be borne in mind that the results obtained from this study may differ from the reality because smoke was excluded from the experiments. Smoke imbedded in the rubber could retard the transportation of water inside the rubber to the surface and result in a delayed processing time. However, the advantageous effect of lower inlet moisture in actual smoking was proved by the green and dry firewood smokings.

## CONCLUSION

The curing characteristics of rubber sheets with respect to surrounding humidity, air flow rate and loading density were examined. The curing time was inversely proportional to the relative humidity of the inlet air. The effect of air flow rate was determined at 40% relative humidity and specific air flow rates of 0.012-0.080 $m^3/h$ kg. Within this range of air flow rate, there was no clear evidence of the role of the air flow rate. An experiment with the loading density equal to the actual practice in the factories was conducted at 40% relative humidity and a specific air flow rate of 0.016 $m^3/h$ kg. At conditions similar to actual practice, but using drier inlet air, the curing time was found to be 2700 min (45 h) which is about 40% of that currently needed in the factories (116 h) [3]. Comparative experiments with dry firewood and green firewood demonstrated that moisture in the firewood significantly affected the smoking time. This leads to the strong conclusion that dehumidification of the inlet air would be a promising technique for accelerating the rubber smoking process.

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