CHAPTER FOUR
FACTORS AFFECTING RUBBER DRYING PROCESS

SUMMARY

Factors affecting the drying of rubber sheet was studied. Experiments were carried out on batches of 15 kg rubber tested in an environmentally controlled chamber. Parameters designed for the study were relative humidity (RH) of inlet air, air flow rate and loading density (kg of rubber/m^3 of chamber). Drying time was inversely proportional to the relative humidity of the inlet air. Relative humidity of 40% at room temperature (30-32°C) is desirable. Air flow rate had minimal effect on the drying behaviour of the rubber sheets. A test with loading density similar to and specific air flow rate slightly less than the actual practice but inlet air of 40% RH resulted in a drying time of 40% of that is currently required in the factories. Experiment on 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 1 day but consumed more pieces of firewood.

4.1 INTRODUCTION

Results of the monitoring of the rubber smoking process (Chapter 3) revealed a significant amount of water inherent in the inlet air and firewood. Generally, the per-batch smoking time is in the range of 5-9 days depending on the seasons (dry or wet) which eventually reflects the adverse effect of moisture in the atmosphere. It was estimated that, for a batch of smoking, there are about 2 tons and 5 tons of water inherent in the combustion air flowing through the smoking room (via furnace) during the dry and wet seasons, respectively, while the moisture removed from the rubber is approximately 1.2 tons only [18]. Consequently, it was envisaged that the smoking time can possibly be reduced, and hence increase the productivity, by the dehumidification of the combustion air [11,18]. However, the drying behaviour of rubber sheets with respect to the humidity surrounded them is still quantitatively unclear. In general, the decrease of the relative humidity will result in shorter drying time.

This chapter gives results of study, in a laboratory scale, on the effects of the air humidity as well as other factors such as air flow rate and loading density (kg of rubber/m^3 room). Results of full-scale experiment when the smoking rooms were fired with green firewood and dry firewood are also presented.

4.2 FACTORS AFFECTING RUBBER SHEET DRYING PROCESS

It is necessary to experimentally verify the effects of parameters influencing the rubber drying process. Parameters of particular interest are inlet air humidity, inlet air flow rate and loading density (kg of rubber/m^3 of room)

4.2.1 Materials and Methods

An environmentally controlled chamber, as shown schematically in Figure 4.1, 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

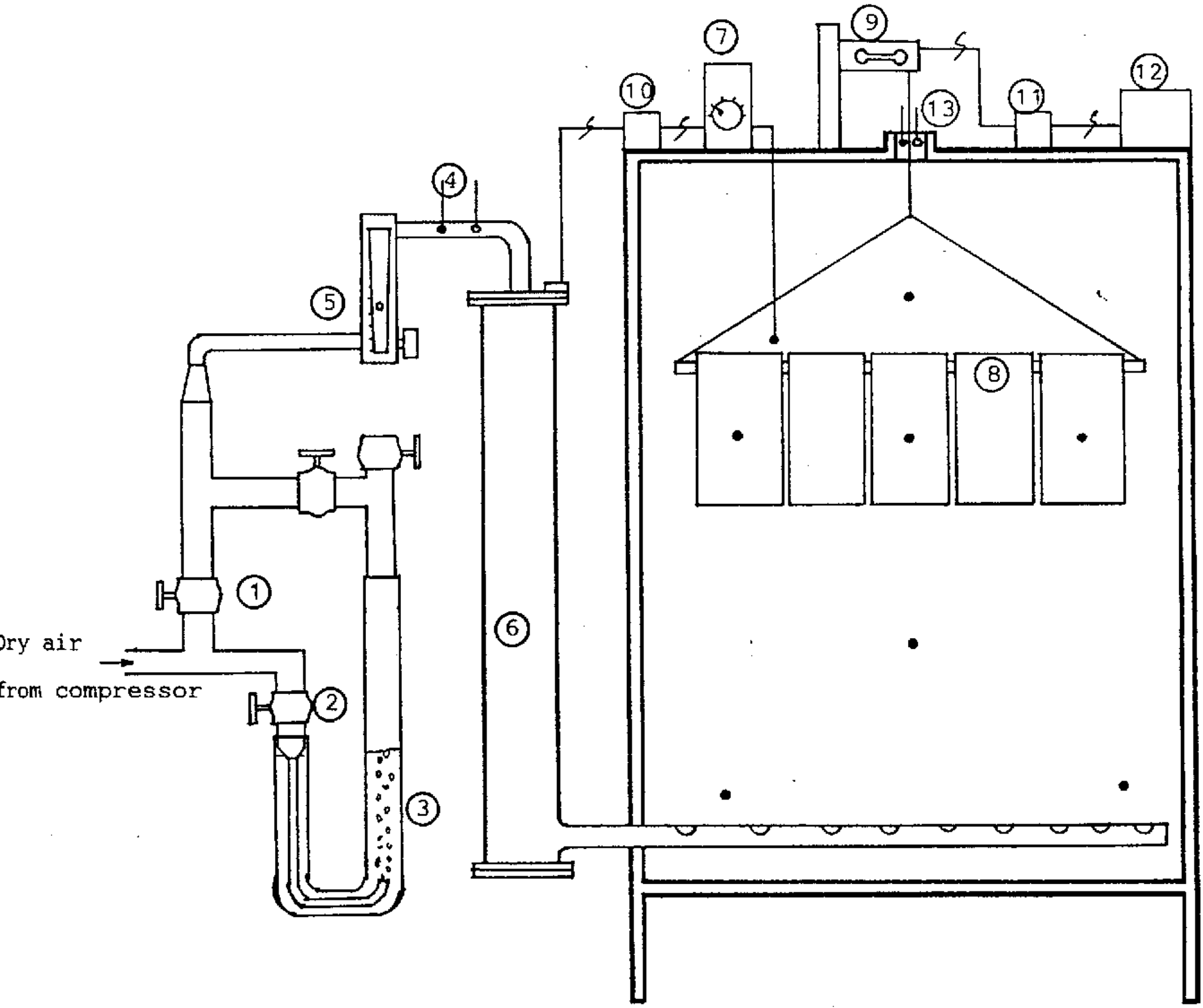

Figure 4.1 Environmentally controlled chamber

(● 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

sheets were graded by an experienced person so that consistent thickness and moisture content of every sheets were attained. The nominal size of the 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 placing 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 Figure 4.1, 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 were described in Table 4.1.

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 (Chapter 3). In order 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 varied the inlet air relative humidities from 80% to 20%. Likewise, the 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 an 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 in stead 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 clear appearance of the whole and every sheets.

Table 4.1 Programme of Experiments

Experiment	RH (%)	Air flow rate (m^3/h)	Mass of 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	123.90

4.2.2 Results and Discussion

The experiment results are presented quantitatively in Table 4.2. In general, the moisture removed from the rubber was less than 5% of its initial weight.

4.2.2.1 Effects of inlet air moisture

Experiments 1-4 gave the effects of the inlet air moisture on the drying time of the rubber sheets. The relative humidities in the study were 80%, 60%, 40% and 20% at ambient temperature of 30-32 °C. The corresponding figures for the test cell temperature (65 °C) were 15%, 11%, 7% and 3.5%, respectively. Figure 4.2 shows the drying characteristic of the rubber sheets at various relative humidities of the inlet air. It is obvious that the lower relative humidity resulted in shorter drying time. High drying rate, due to vaporization of the wetted surface, at the beginning was apparent for every experiments. When the surface of the sheet was still relatively wet, the sheet was 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 sheet to provide latent heat of evaporation of the water. Heat transfer and, therefore, evaporation depend on the temperature difference between the air and the sheet. Another word, the drying rate at this stage is proportional to the difference between the wet and dry bulb temperatures of the surrounding air. That is, relative humidity is a prime factor at this stage.

Drying times for the experiments with 60%, 40% and 20% RH were 76.6%, 59.6% and about 50% of that for 80% RH experiment, respectively. It is interesting to find that high portion of steady-weight period occurred in the high humidity cases, Figure 4.2. Drying mechanism in the steady-weight period is diffusion, which is influenced by the humidity of the surroundings and the temperature. The humidity affects the equilibrium moisture content while the temperature affects the diffusion.

One might argue that the variation of the drying times in experiments 1-4 was just the effect of the differences in initial

Table 4.2 Results of Experiments

Parameter	Expt	RH (%)	Air flow rate(m^3/h)	Moisture removed (%)	Drying time (min)	Relative drying time (%)
	1	80	0.3	3.65	4230	100
	2	60	0.3	2.60	3240	76.6
moisture*	3	40	0.3	2.37	2520	59.6
	4	20	0.3	2.09	2040	48.2
	5	20	0.3	3.24	2160	51.1
	6	40	0.18	3.5	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	4.7	2460	89.1
Loading density**	9	40	2.01	4.6	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.

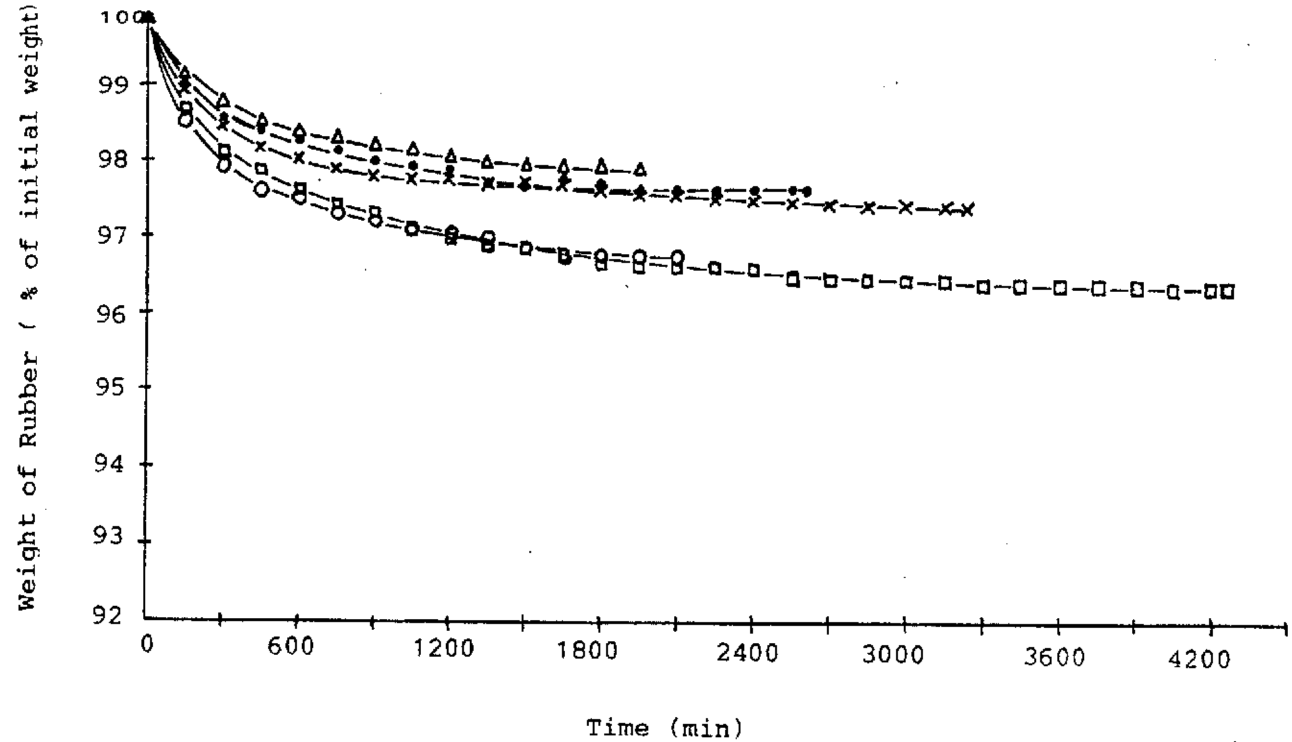

Figure 4.2 Effects of inlet air relative humidity on drying time

□ 80% RH, Drying time 4230 min, Final weight 96.35%

× 60% RH, Drying time 3240 min, Final weight 97.40%

● 40% RH, Drying time 2520 min, Final weight 97.63%

△ 20% RH, Drying time 2040 min, Final weight 97.91%

○ 20% RH, Drying time 2160 min, Final weight 96.76%

moisture of the rubber, because, accidentally, rubber with higher moisture was tested with higher air humidity (see Table 4.2). An experiment with 20% relative humidity was repeated (experiment 5) with the rubber as moist as that of experiment 1. The result of experiment 5, which was included in Figure 4.2, confirmed the advantageous effect of the low relative humidity of the inlet air.

Since the end of the experiment was determined by the clear appearence of the whole and every sheets, the inconsistent or nonuniform initial condition of the rubber sheets (in the same test) would inevitably affect the result. That is, the drying time of each experiment depends solely on the thickest and moistest sheet. However, the irregularity of the samples seemed insignificant as the drying time, Figure 4.2, strongly depended on the inlet air humidity.

4.2.2.2 Effects of air flow rate

Results from experiments 1-5 revealed that the less humidity of the inlet air used, the shorter drying time was obtained. However, the minimum relative humidity (20% RH) may not be economically practical. There was only 10% difference in drying time between the 40% RH and 20% RH experiments. The advantage of shorter drying 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 drying behaviour of the sheets were determined by keeping the relative humidity of the inlet air constant at 40% but varied the flow rate as shown in Table 4.2.

Surprisingly, the results, Figure 4.3, showed that the air flow rate had little effect on the drying time. The experiments in this series had maximum air flow rate of 6.7 times of the minimum flow rate but the difference in the drying 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

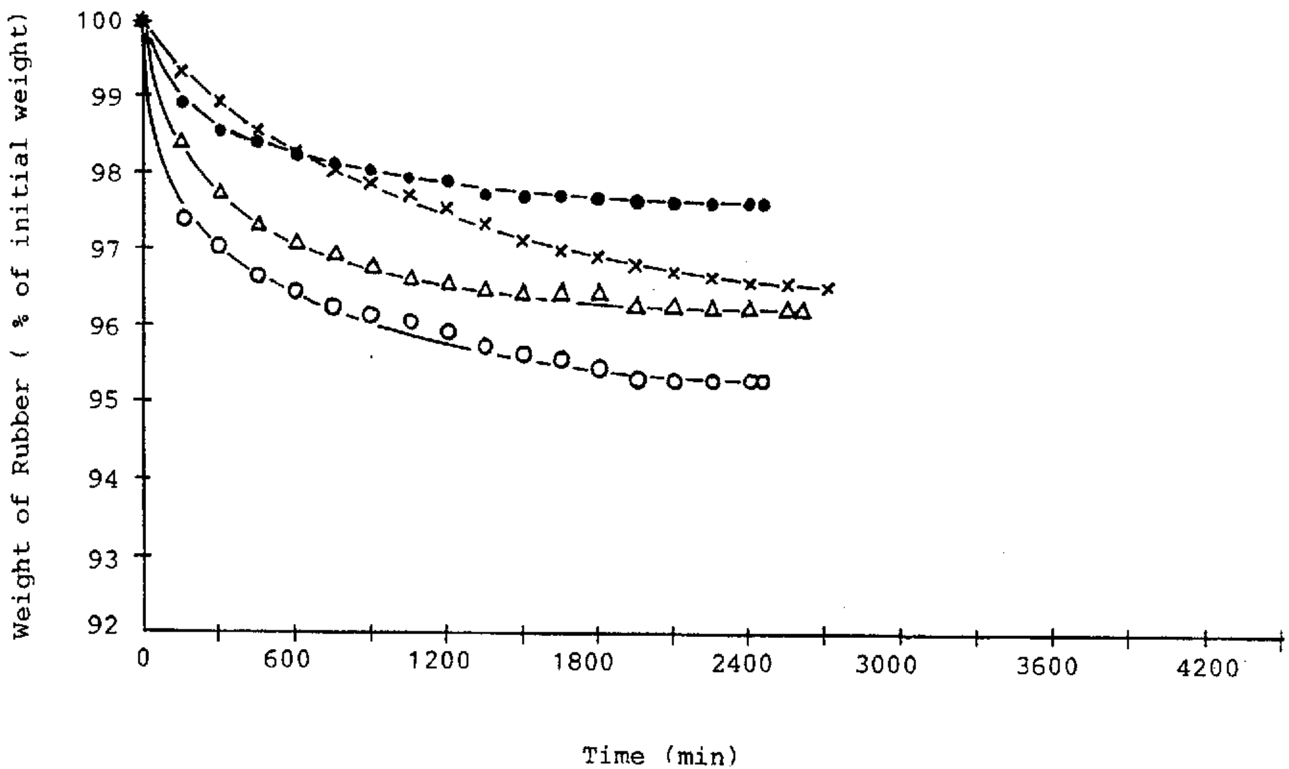

Figure 4.3 Effects of air flow rate on drying time (40% RH)

× 0.18 m^3/hr, Drying time 2760 min, Final weight 96.50%

● 0.30 m^3/hr, Drying time 2520 min, Final weight 97.63%

Δ 0.60 m^3/hr, Drying time 2640 min, Final weight 96.24%

○ 1.20 m^3/hr, Drying time 2460 min, Final weight 95.30%

ventilation fans was done in some factories. However, it did not only fail to serve the objective but also resulted in higher fuel consumption in order to maintain the required room temperature [19]. High air velocity works well for the evaporation (when the rubber is still wet) but not for the diffusion which is the mechanism responsible for the removing of the moisture in its last few percent [20,21]. In actual practice, the combustion air of about 700 m^3/h was already found unnecessarily high [18]. Therefore, if dry air is incorporated in the process, a lower (than 700 m^3/h) capacity air dehumidifier should be used effectively.

4.2.2.3 Drying with high loading density

Loading density has direct effect on hot air circulation inside the room. Although the previous experiments revealed that air flow rate, hence the circulation, had unnoticeable effect on drying time, the final experiment (number 9) was carried out with loading density equal to that is presently practising in the factories (63.73 kg/m^3). 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 Figure 4.4. It is obvious that the drying curve in Figure 4.4 is different from the curves of the low-loading-density ones. Figure 4.4 has lower drying rate at the begining of the process compared with the low-loading-density results. It exhibited no steady weight period at the end neither. The drying time was 2700 min which was in the same range of the low-loading-density experiments.

4.2.3 General Discussion

For rapid drying, the rubber sheets should be as thin as possible (to reduce the diffusion time), high temperature and low humidity should be used throughout and in the early stage high air flow rate should be advantagous (for rapid evaporation). It was reported that air speed of 0.5 m/s gave an evaporation rate two to three times that obtained under natural convection condition [4]. Air speed that passing along the rubber sheets in this experiment was far below the figure quoted in the literature. There are practical limitations to

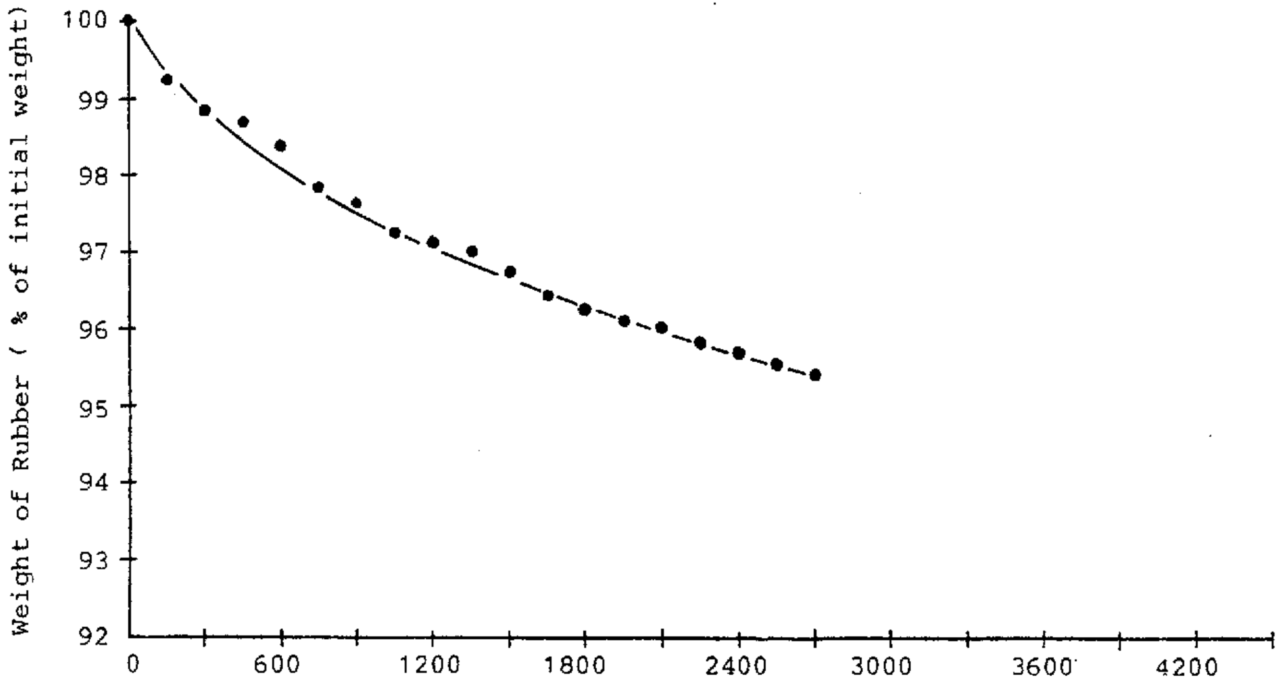

Figure 4.4 Result of actual room density (63.73 kg/m^3)
40% RH, specific air flow rate 0.016 $m^3/hr/kg$,
Drying time 2700 mim, Final weight 95.40%

achieve 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. Extremely high temperature will damage the sheets by blistering. The high air flow rate will increase firewood consumption.

Results from the experiments indicate that the use of dry air should greatly affect the rubber smoking industry in the senses of increasing the productivity and decreasing the firewood consumption. Change in production cost depends on the cost of firewood that can be saved and the cost required for dry air acquisition. 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 are 9.6 kg/h and 4.9 kg/h in order to obtain 40% relative humidity at 32 °C. Dehumidifier that possesses such capability and economically viable has therefore become the ultimate goal of this project. 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 impeded in the rubber could retard the transportation of water inside the rubber to the surface and results in delayed processing time.

4.3 TRIAL TEST WITH GREEN AND DRY FIREWOOD

4.3.1 The Experiment

Green wood contributed substantial amount of water (about 24% see Table 3.3) to the process which eventually is not desirable for drying the matter. Effect of water contained in the firewood was determined by smoking the rubber in two rooms simultaneously (in order to achieve identical ambient condition) but using green firewood in one room and dry firewood in the other. Green and dry firewood were sorted according to their appearence, storage history (the ones down under in the stock pile were usually the dry ones). Every firewood was weighed and cut in the middle for a slice of about 1 cm in thickness. The slices were weighed and dried in an oven at 70 °C until constant weight was obtained. Moisture content of every pieces of firewood were subsequently calculated. Rubber sheets in the smoking rooms were regularly observed to prevent unnecessarily prolonged smoking and hence obtain the correct smoking time. The two smoking rooms in this experiment were room number 3 (green wood) and 4 (dry wood). The firing started at 4 pm of October 11, 1991.

4.3.2 Results and Discussion

Summary of firewood used is tabulated in Table 4.3. Assuming that the rubber in the two rooms had the same initial conditions, Table 4.3 implies that smoking time can be shortened by 19% if dry firewood is used. The actual moisture contents of the rubber in the two rooms were not determined in the experiment because there was insufficient data to perform mass balance calculation. However, 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 total mass of firewood used by the two rooms was different, apparently the two rooms consumed the same amount of the "real dry wood". The real dry wood is the total mass of firewood subtracted by the mass of moisture. More dry firewood, in term of pieces, was required in comparison to the green firewood because the dry firewood was burnt at a faster rate. This resulted in two undesirable consequences. Firstly, it caused shorter furnace refill period (2.3 h v.s 3.3 h) and higher number of refill (48 times v.s. 41 times) even though the processing time was shorter (110 h v.s. 135.5 h), (room number 4). More labourious job for the furnace operator is not avoidable. Secondly, the fuel cost will be higher since firewood is being sold on volume basis. But the increase in fuel cost should be insignificant as it contributes only 1-2% of overall production cost [18].

Figure 4.5 shows that the firewood throwing into the furnace of room 4 was always less than that occurred in room 3. The patterns of firewood consumption with respect to time in the two rooms were similar. Accumulative firewood consumption for the two rooms is shown

Table 4.3 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

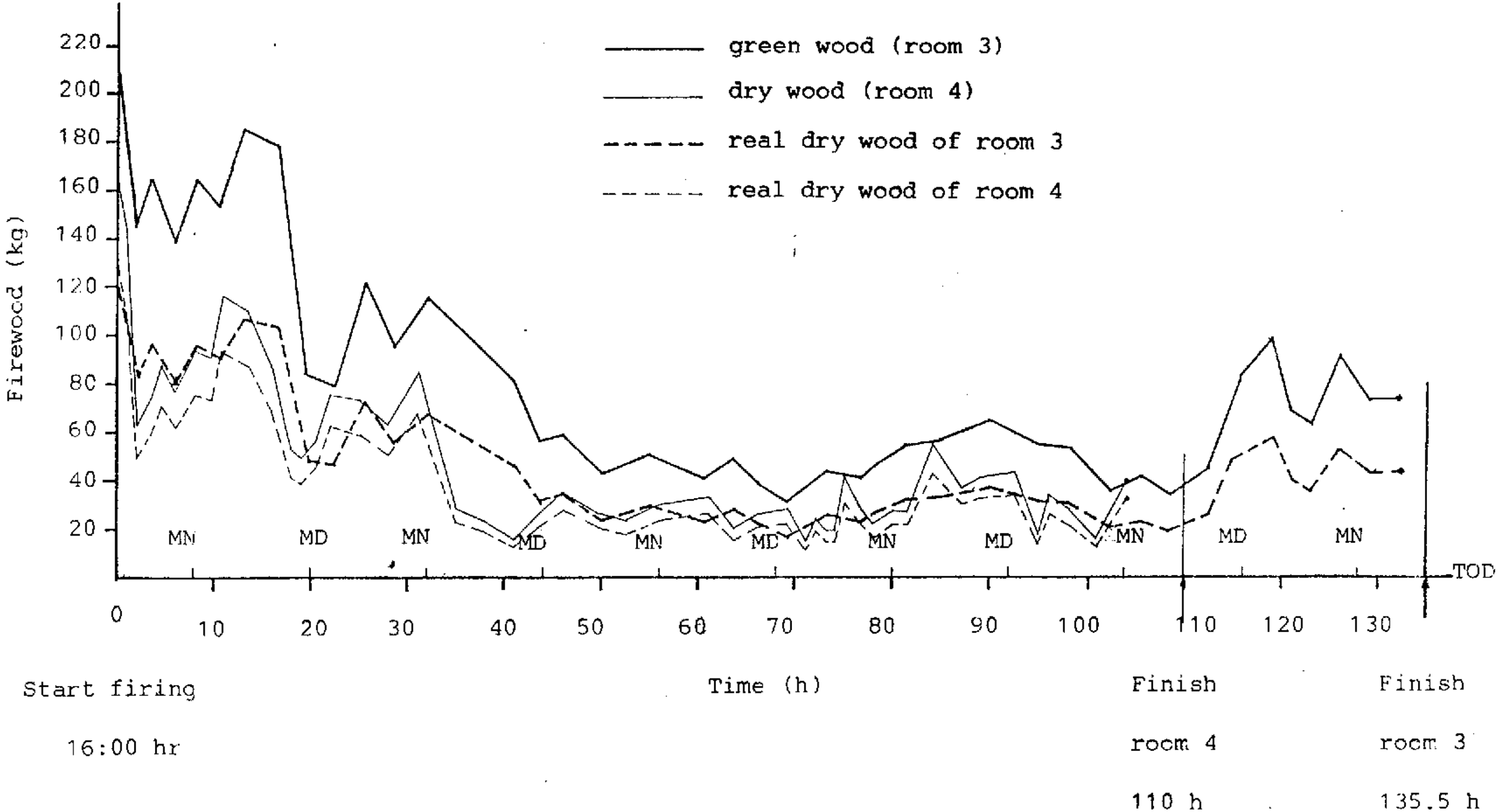

Figure 4.5 Firewood consumption of room #3 (green wood) and #4 (dry wood)
TOD = Time of Day, MD = Mid Day, MN = Mid Night

in Figure 4.6. Figure 4.7 is the humidity ratio of the exhaust of the two rooms. It is obvious that the exhaust of room 3 (green wood) was 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 some instance the temperature in room 4 was too high so that the furnace operator had to put down the fire.

4.4 CONCLUSION

Drying characteristics of rubber sheets with respect to surrounding humidity, air flow rate and loading density were examined. The drying 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 a 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 the conditions similar to the actual practice but used drier inlet air, the drying time was found to be 2700 min (45 h) which is about 40% of that is currently taking place in the factories (116 hr) [18]. Comparative experiment with dry firewood and green firewood demonstrated that moisture in the firewood significantly affected the smoking time. This leads to a strong confidence that dehumidification of inlet air should be a promising technique that accelerates the rubber smoking process.

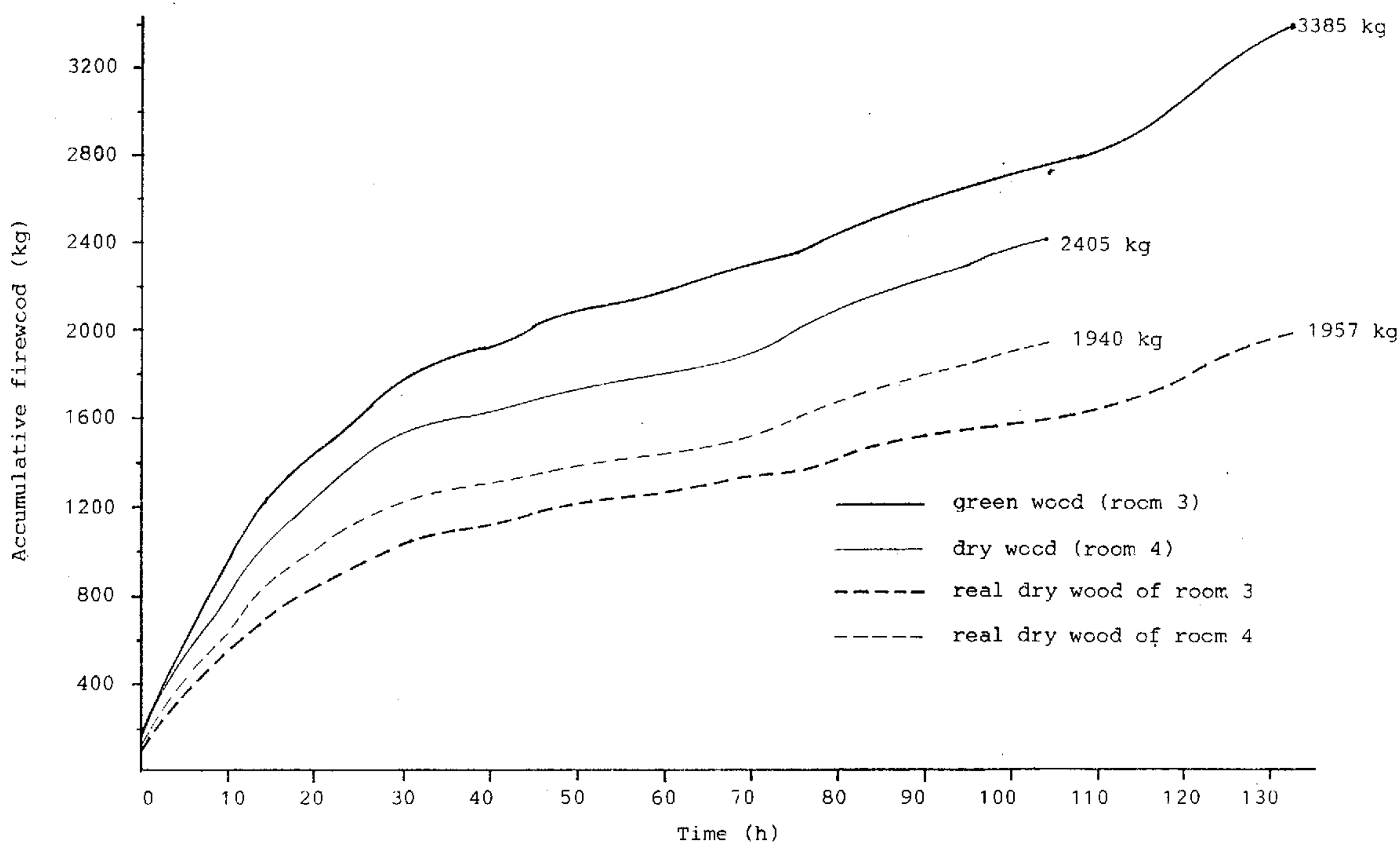

Figure 4.6 Accumulative firewood consumption

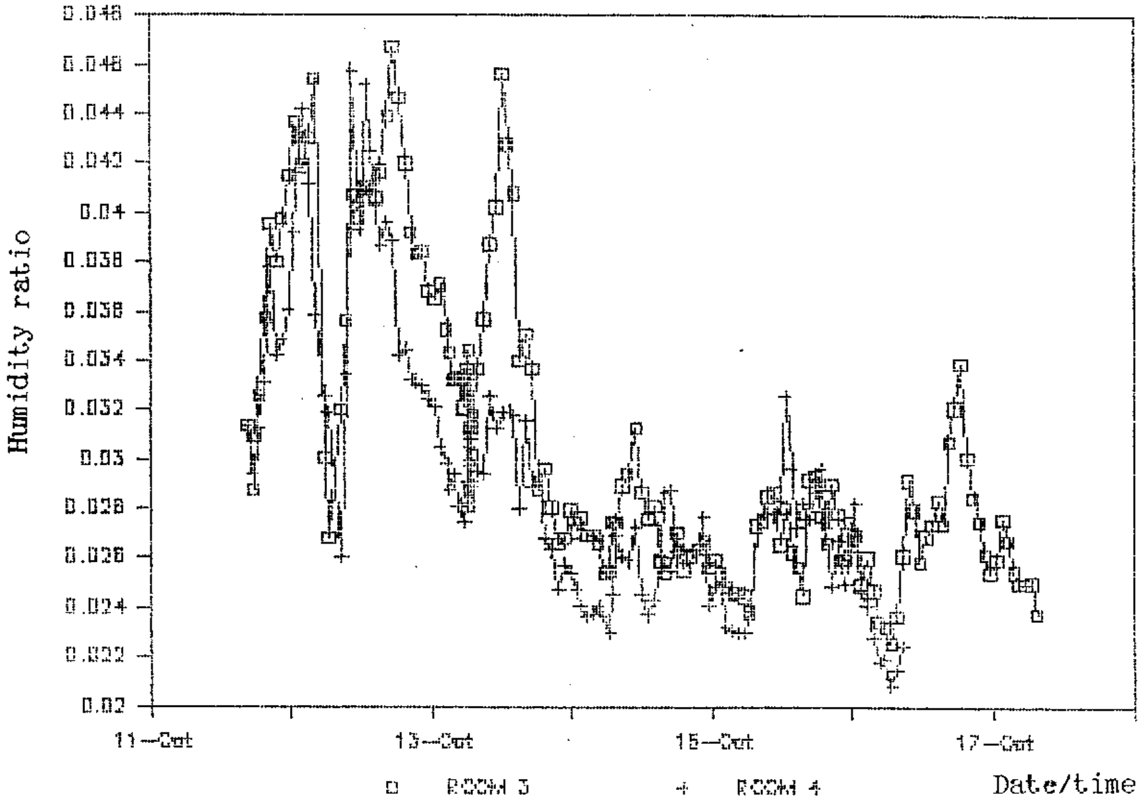

Figure 4.7 Humidity ratio of the gas exhausted from rooms #3 and #4