Monitoring of the Rubber Smoking Process

S. Prasertsan, P. Kirirat, S. Sen-Ngam, G. Prateepchaikul
Department of Mechanical Engineering, Prince of Songkhla University
Hat Yai, Thailand 90110

N. Coovattanachai
Faculty of Engineering, Thammasart University, Rangsit Campus
Patumtanee, Thailand 12121

ABSTRACT

Monitoring of the rubber smoking process was carried out and the results are presented herein. The smoking room in this study had a capacity of 45 tons of rubber sheets and required heat of 20,120 MJ during 116 hours of operation. Only 31% of the input heat was useful. The rest was the lost through conduction (57%) and ventilation (11.8%). However, energy saving measures were not recommended since the financial benefit was very low compared to the overall financial scale of the smoking operation. Water inherent in the exhaust gas was found to be 4.2 tons of which 2 tons, 1 ton and 1.2 tons could be derived from inlet air, firewood and the rubber, respectively. It is believed that dehumidification of the inlet air will significantly increase the productivity by reducing the processing time.

INTRODUCTION

In 1989 seventy six percent of the world rubber production was from Malaysia, Thailand and Indonesia [1]. After Malaysia, Thailand is the second biggest rubber producing country in the world. It was estimated that during the 7th National Economic and Development Plan (1992-1996) the gross rubber production of Thailand will increase from 1.30x10^6 tons to 1.58x10^6 tons as shown in Table 1.

Table 1. Projection of Thailand's rubber production during 1992-1996.

Year	Planted Area (x10^6 ha)	Production (x10^6 ton)	RSS* (x10^6 ton)
1992	1.89	1.30	1.09
1993	1.91	1.37	1.12
1994	1.93	1.44	1.15
1995	1.95	1.51	1.16
1996	1.96	1.58	1.18

*RSS = Ribbed Smoked Sheet Rubber
Source: Rubber Research Institute, Ministry of Agriculture and Cooperatives, Bangkok, 1992.

About 80% of the rubber produced in the country is ribbed smoked sheet (RSS) rubber which makes Thailand the biggest RSS producing and exporting country in the world. In 1989 Thailand exported 920×10^3 tons of RSS compared to 278×10^3 tons and 152×10^3 tons for Malaysia and Indonesia, respectively. During 1980-1989 Thailand increased her RSS exports by 168% [1].

RSS is a solid form of rubber product. Hot gas and smoke obtained from wood burning are used to cure the rubber sheets in smoking rooms. The smoke acts as a disinfectant which renders the rubber less liable to mould attack. Although Thailand is the biggest RSS rubber producer, scientifically, the study of the rubber smoking technique has received very little attention in the country. The design and operation of smoking rooms has merely relied on past experiences. Development of the smoking process has generally been based on the trial and error method. This has resulted in the existence of two types of smoking room, namely, single layer and double layer rooms. Surveyed data revealed that the performance of the single layer rooms is far better than the double layer rooms [2]. However, there is no solid evidence by which one could conclude that the single layer rooms are being operated at optimum conditions. Furthermore, there are signs that current performance standards can be improved upon [3]. However, all characteristics of the smoking process have to be thoroughly investigated before improvements can be made. This article presents the results obtained from the monitoring of a rubber smoking room.

OVERVIEW OF RUBBER SMOKING ROOM AND SMOKING PROCESS

Smoking Room

There are two types of smoking room, called single and double layer rooms (Figs. 1 and 2). Single layer rooms have one floor while double layer rooms have two. The double layer type, which is an old design, has timber or brick walls. For the last 10-15 years, large, one-layer rooms have been considered the better design. Single layer smoking rooms are now being adopted in the

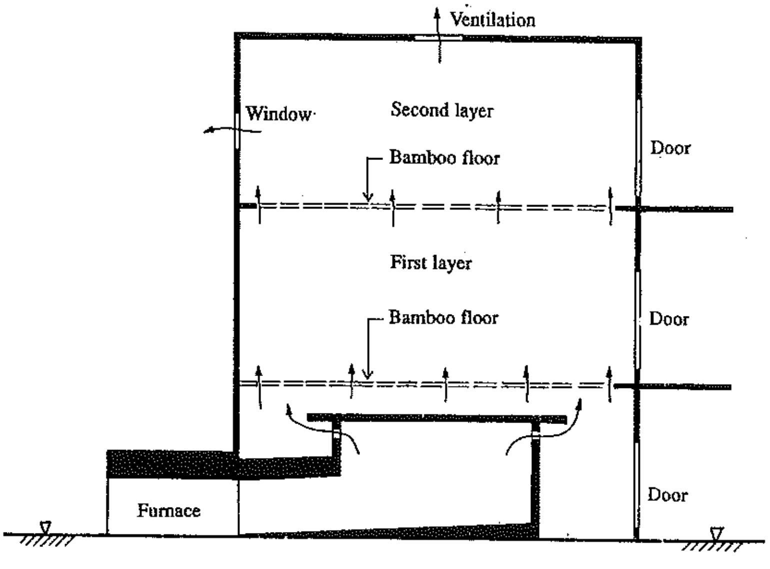

Fig. 1. Double layer room.

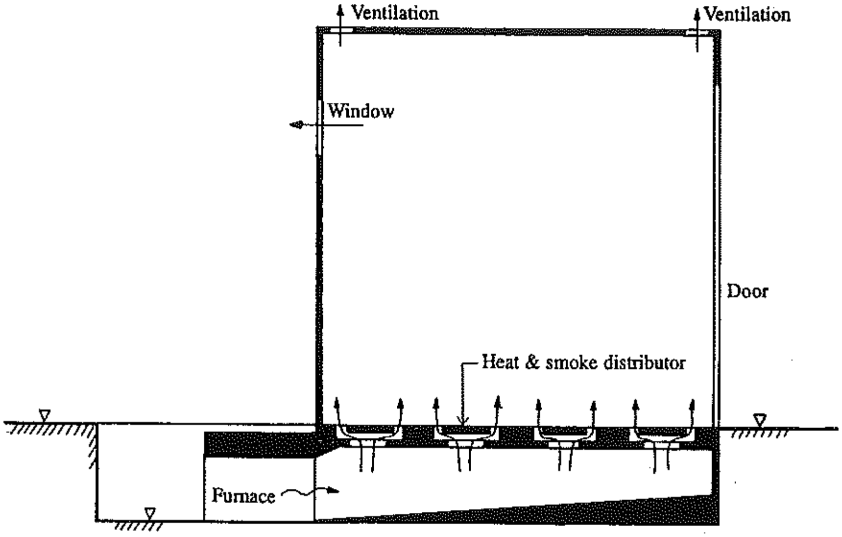

Fig. 2. Single layer room.

new factories and they have become popular because their performance is superior to that of the double layer rooms. The rooms are constructed of brick and mortar. The front wall is typically a steel gate for loading and unloading the rubber. Ventilating windows are on the rear wall and the ceiling. The rooms are generally equipped with temperature sensing elements for temperature monitoring and control. Heat and smoke distributing tunnels are on the floor. The rubber sheets are hung on bamboo stems which are subsequently placed on 2x2x4.5 m^3 steel crates. A forklift truck is used to manoeuvre the crates into and out of the rooms. For the present study, monitoring of this work was undertaken for the single layer room type only. A description of the room is shown in Fig. 3.

Furnaces are normally located at the rear of the rooms. Hot gas and smoke are conveyed through the distributing duct and grid into the room. The combustion rate is controlled by an adjustable steel gate in the front of the furnace so that the temperature in the room can be controlled.

Smoking Process

Latex collected from rubber plantations is coagulated with formic acid. Before coagulation sets in, aluminium partitions are inserted vertically in slots in the coagulating tank. After storage for a few hours, the soft thick gelatinous slabs are compressed by passage through four to six rollers to remove water and produce sheets of about 5 mm thickness. The last pair of rollers are grooved and thus produce the characteristic criss-cross rib markings on the sheet. This increases the surface area and facilitates drying.

The rubber smoking factories acquire ribbed unsmoked rubber sheets through local dealers. Skilled workers in the factories visually grade the rubber sheets according to the moisture content and thickness. The sheets are subsequently washed manually in a pool or by a machine before entering the smoking rooms where they are dried and cured for 5-9 days depending on the moisture, thickness and season. At the beginning, all windows and ventilating ports (of the smok-

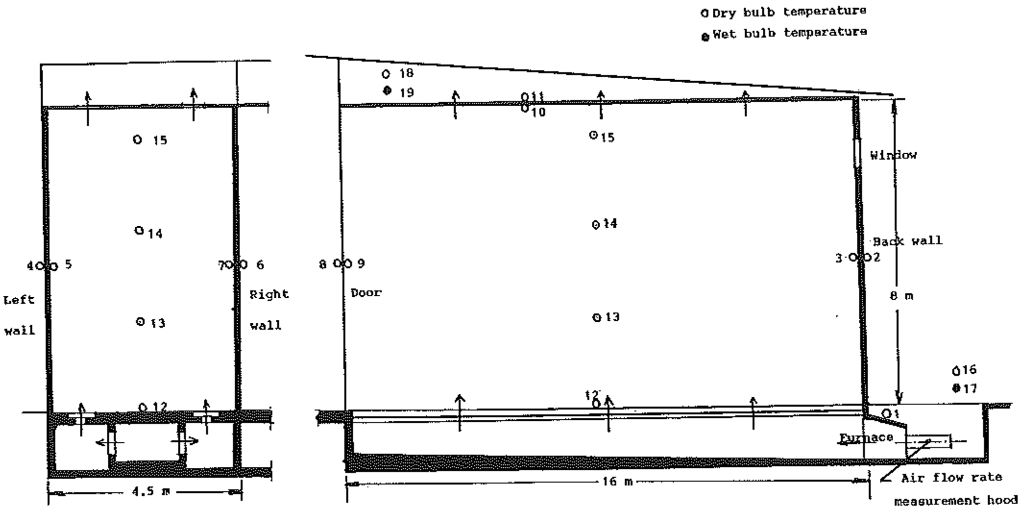

Fig. 3. Description of the smoking room and parameters to be measured.

ing room) are open and the firewood is burnt at a high combustion rate to bring up the room temperature to 40-50°C in a short period. After reaching the required temperature, ventilation is prohibited and the opening of the furnace is adjusted to control the firewood burning and hence keep the temperature in the room at about 70°C. Typical room temperatures are illustrated in Fig. 4. The process continues until the rubber sheets are dried and cured. The smoked sheets are then pressed to form bales of about 110 kg, wrapped with the sheets and coated with talc to hinder bale-to-bale adhesion.

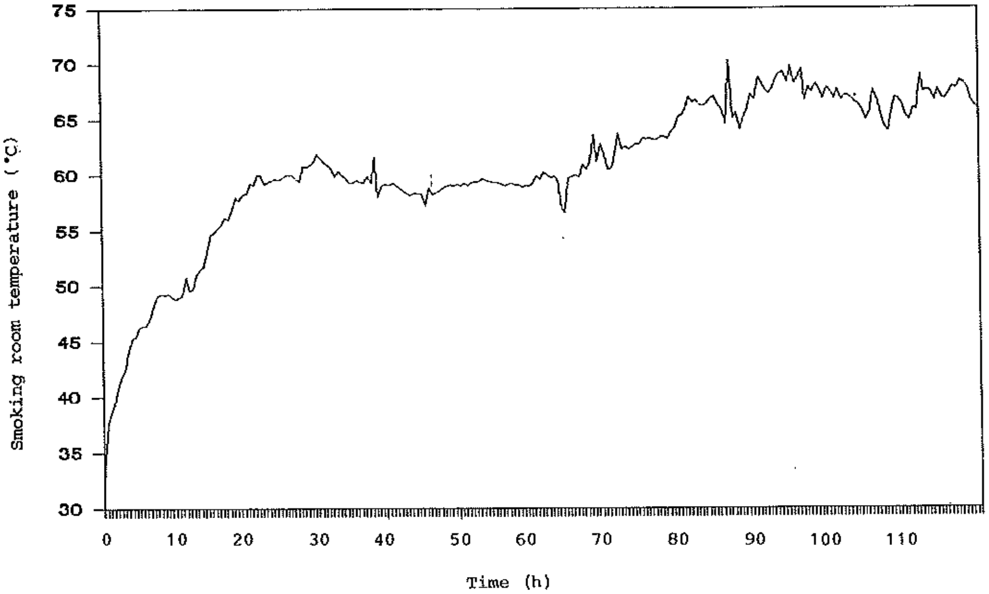

Fig. 4. Typical smoking room temperatures (average of 3 levels in the room).

MONITORING OF SMOKING PROCESS

The monitoring of the rubber smoking process was conducted during an actual smoking practice at Southland Rubber Co. Ltd., Bangklum, Hat Yai, Southern Thailand. The factory consists of two rows of ten smoking rooms each. Four of the rooms, have one of the side walls open to the atmosphere. It was expected that such rooms would be operating at low energy efficiency. Hence, one of these rooms was selected for monitoring.

Under normal operating conditions, the parameters measured were temperatures at various locations as depicted in Fig. 3 (type k thermocouple and Omega HH81 digital thermometer, Omega Engineering, USA), moisture contents of inlet and exhaust air (wet bulb and dry bulb method), inlet air flow rate (calibrated vane type anemometer, Airflow Development Ltd., UK), firewood consumption and combustion products (samples were taken by a vacuum pump and analysed by a Fyrite II combustion analyser, Bacharach, USA). Data were acquired every 30 minutes. Three experiments were carried out during 3-24 May 1991.

ENERGY ASPECT OF SMOKING PROCESS

Energy flowing into the system was determined from the heating value of the firewood. Energy flowing out of the system was calculated from the heat conducted through the walls and exhaust gas. The balance of energy was the sensible heat of the rubber and the room structure and latent heat of the water evaporated from the rubber. Calculations were based on 42.2% moisture content [4] and 4.1% ash content [5] of the firewood. The heating value of firewood (rubber wood) was taken as 13,600 kJ/kg [6]. Thermal properties of materials involved were obtained from some well known sources [7,8]. Equations used in the calculation are given in the Appendix.

The basic data are described in Table 2 while the analyzed results are presented in Table 3.

Average specific firewood consumption was 54 kg/ton of rubber. The smoking process lasted about 116 hours (4.8 days). Table 3 revealed that only 31% of input energy was used in the rubber drying process while 57% was lost through the four walls and 11.8% via ventilation. Typical heat lost through the room structure is characterized by Fig. 5. Negative heat flow occurring in some period was the result of heat gained through the right wall from the adjacent room. The overall heat transferred through the right wall is negative (input heat). It must be noted that the positive heat loss of the right wall in Table 3 was derived from the positive portion of Fig. 5(a) only. Energy lost through the door was relatively steady while the losses through the left and back walls varied with the time of day. The two losses had a similar pattern which indicated the influence of surroundings as will be discussed later. However, the total loss through room structure was

Table 2. Basic data of experiments.

Description	Test 1	Test 2	Test 3
D/M/Y	8-13/5/91	13-18/5/91	18-24/5/91
Smoked rubber (kg)	45,526.0	43,850.0	47,322.0
Water removed (kg)	1,312.0	1,255.6	1,091.2
Fuelwood (kg)	2,698.0	2,460.0	2,225.0
Smoking time (h)	166.5	110.0	122.5

Table 3. Energy analysis for the smoking process.

	Test			
Energy (MJ)	1	2	3	Average
Input energy*	22245.5 (100)	19510.0 (100)	18604.5 (100)	20120.0 (100)
Useful energy				
Latent heat	3082.3 (13.8)	2949.3 (15.1)	2560.2 (13.8)	2863.9 (14.2)
Rubber sen. heat	3367.5 (15.1)	3404.9 (17.5)	3430.6 (18.4)	3401.0 (16.9)
Stored energy				
Left wall	206.1 (0.92)	141.7 (0.70)	172.7 (0.93)	173.5 (0.86)
Right wall	232.9 (1.05)	247.2 (1.3)	122.3 (0.65)	200.8 (1.0)
Back wall	47.5 (0.20)	21.5 (0.11)	40.5 (0.22)	36.5 (0.18)
Door	6.4 (0.03)	2.3 (0.01)	3.2 (0.02)	4.0 (0.02)
Ceiling	16.5 (0.07)	11.5 (0.06)	11.1 (0.06)	13.0 (0.06)
Floor	818.5 (3.7)	851.2 (4.4)	881.8 (4.7)	850.5 (4.2)
Energy losses				
Left wall@	4478.5 (20.1)	7747.4 (39.7)	6318.7 (34.0)	6181.5 (30.7)
Right wall	607.0 (2.7)	852.2 (4.4)	576.9 (3.1)	678.7 (3.4)
Back wall@	2638.0 (11.8)	2940.5 (15.1)	3385.9 (18.2)	2988.1 (14.8)
Door@	1424.0 (6.4)	1546.6 (7.9)	1653.9 (8.9)	1541.5 (7.7)
Exhaust	2059.4 (9.2)	2447.5 (12.5)	2600.9 (14.0)	2369.3 (11.8)
Uncountable	3260.9 (14.0)	–3653.8 (–18.0)	–3154.2 (–16.9)	–1182.4 (–5.9)

Figures in brackets are %

* Includes heat gain from the adjacent room at the beginning

@ Walls that open to surroundings

considerably constant with time as was verified by a linear relationship between accumulative loss and time, Fig. 5(b). A similar characteristic was also found for the exhaust loss as shown in Figs. 6(a) and (b). The low frequency fluctuation in Fig. 6(a) was mainly due to variation of the reference temperature (day-night ambient temperature). The ceiling was enclosed by the roof and the space-in-between was filled with hot exhaust gas. Both surfaces of the ceiling apparently had the same temperature. Hence conduction loss of the ceiling was negligible. It was not possible to measure heat lost through the floor and roof. These losses were incorporated into the unaccountable loss category. The amount of heat due to thermal inertia of the room structure was only 6%. Economic analysis showed that it was feasible to insulate the left and back walls [4]. These two walls are open to surroundings and have areas of 16x8 m^2 and 4.5x8 m^2, respectively. Although a higher percentage of heat loss occurred on the left wall, the loss intensity of the left wall is lower (48.3 MJ/m^2) than that of the back wall (83.0 MJ/m^2). Furthermore, only the loss through the back wall is common in all rooms. Consequently, it is likely that if thermal insulation is thought to be necessary, it is appropriate for the back wall only.

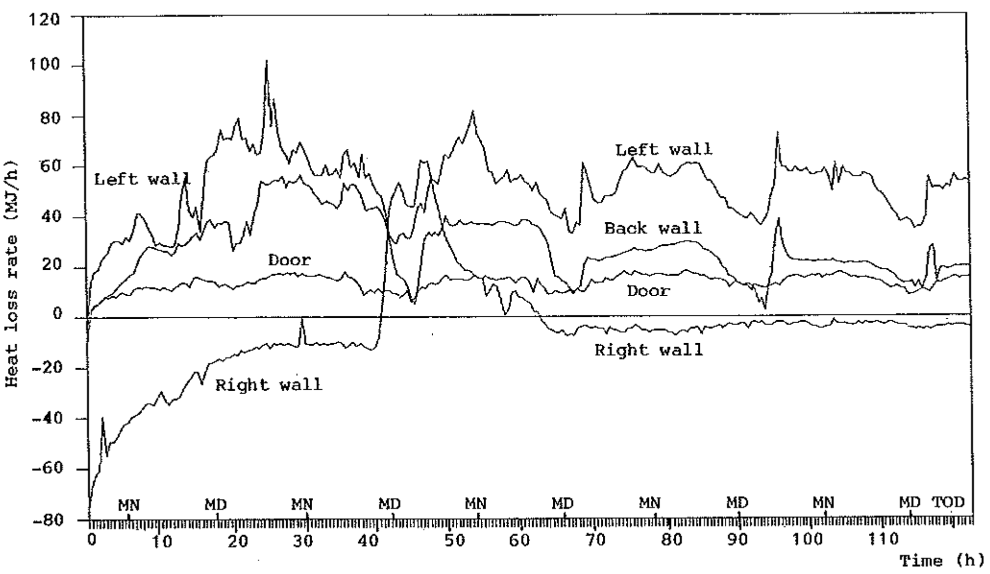

Fig. 5(a). Typical heat loss rate through walls.

TOD = Time of day

MD = Midday

MN = Midnight

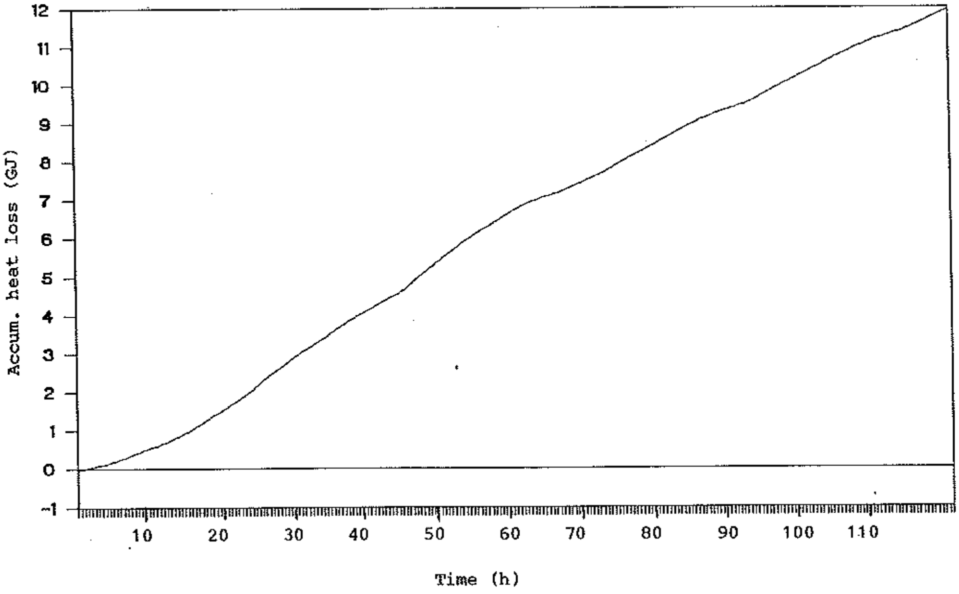

Fig. 5(b). Typical accumulated heat loss through walls.

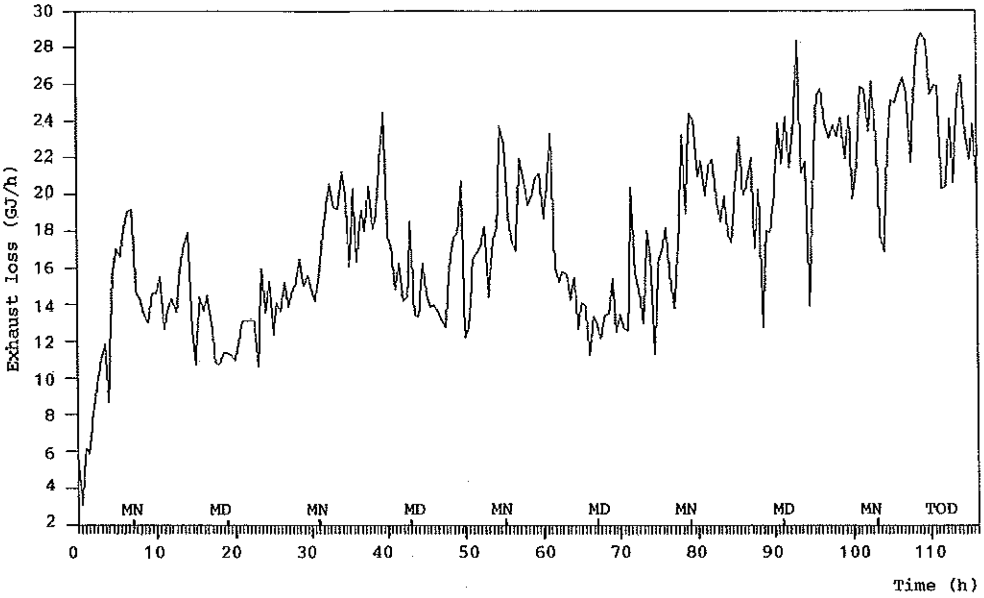

Fig. 6(a). Typical exhaust loss calculated with reference to surroundings.
TOD = Time of day
MD = Midday
MN = Midnight

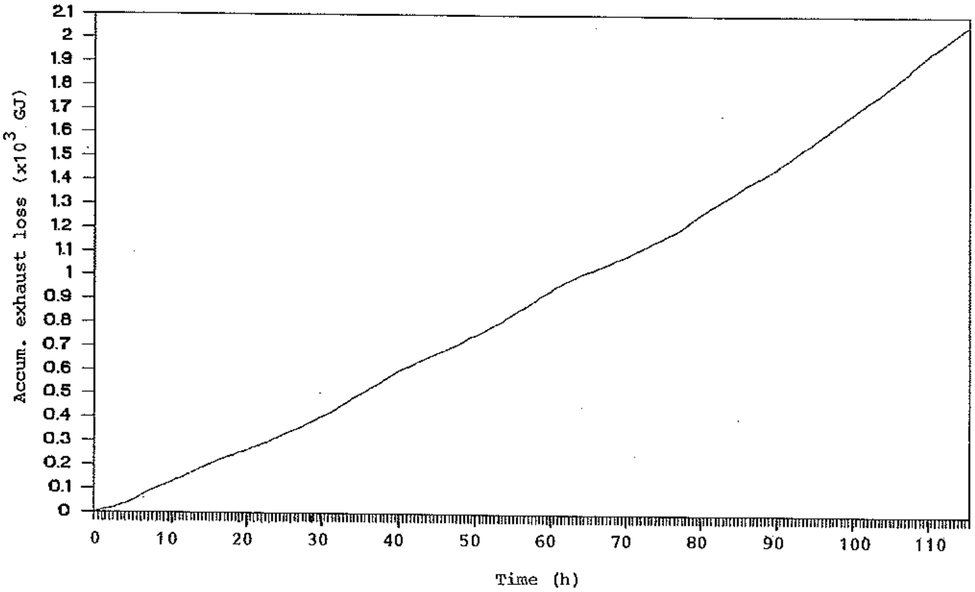

Fig. 6(b). Typical accumulated heat loss via the exhaust.

MOISTURE ASPECT OF SMOKING PROCESS

Apart from smoking, which is the process that renders the rubber less liable to mould attack, drying is another important process. From Table 2, it is obvious that the raw material was considerably dry. Water removed from the rubber accounted for only 2.7%. It must be noted that in this analysis the amount of water removed from the rubber was obtained indirectly, i.e., by subtracting the amount of exhausted water by water input (inlet air and firewood moisture). However, measurement of weight loss of over 100 rubber sheets agreed well with this indirect calculation [9].

The mass of water involved in the smoking process was calculated from the moisture ratio of the inlet and exhaust air, mass flow rate of air into the room, moisture content of the firewood and the firewood consumption. Results are tabulated in Table 4.

Table 4. Water in the smoking process.

Water (kg)	Test 1	Test 2	Test 3	Average	Contribution (% of exhaust)
Exhaust+	4460.9	4180.6	4200.5	4280.7	–
Inlet air+	1995.0	1897.7	2174.0	2022.2	47.2
Fuelwood*	1154.0	1027.3	935.3	1038.9	24.3
Rubber@	1311.9	1255.6	1091.2	1219.5	28.5

\+ Calculated from wet bulb and dry bulb temperatures
* Calculated from moisture content 42.2% wet basis [4]
@Calculated from mass balance

There were 4.28 tons of water released through ventilation, of which 2.02 tons, 1.04 tons and 1.22 tons were water from inlet air, firewood and rubber, respectively. That is, only 28.5% of the total water involved in the process was contributed by the rubber while 24.3% and 47.2% were came from the firewood and inlet air, respectively.

Figure 7 showed that the humidity ratios of the inlet air and the exhaust have a similar trend of low-frequency fluctuation. The rise and fall of the humidity ratios were affected by time of the day (day or night). The fluctuation of the exhaust humidity, while the exhaust temperature was relatively constant, implied that the lower humidity period, the exhaust should have absorbed more water if it had been allowed to do so. This means that the circulating time of the hot gas in the room can be extended so that it can effectively dry the rubber. In other words, inlet air flow rate was unnecessarily high. As time elapsed, a greater difference between the inlet and exhaust humidity ratios was apparent. This can be explained by the increasing drying capability of hot gas due to higher temperature (lower relative humidity), as has been shown in Fig. 4. Typical accumulative mass of water is shown in Fig. 8. During the first 16 hours, the drying rate of the rubber was very low as the room temperature was building up to 55°C. Although Figs. 4 and 8 represent the results of one test only, a similar trend was observed in the other two, but the corresponding times, at which the effective drying occurred, were 15.5 hr (48°C) and 15.0 hr (52.5°C).

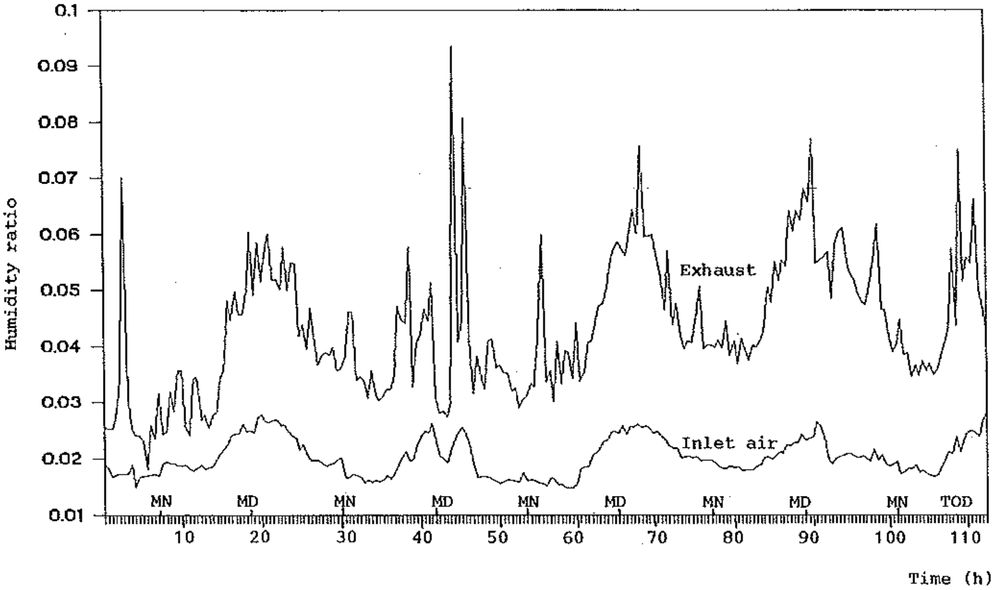

Fig. 7. Typical exhaust and inlet humidity ratios.
TOD = Time of day
MD = Midday
MN = Midnight

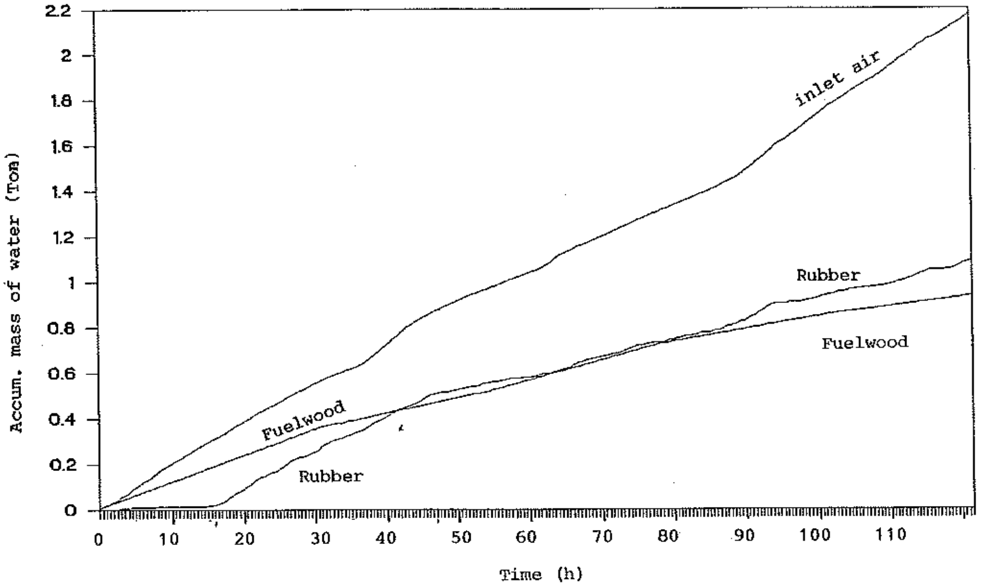

Fig. 8. Typical accumulated mass of water emitted by firewood, extracted from rubber and admitted with inlet air.

GENERAL DISCUSSION

If energy conservation is the major concern in energy management, it is likely that the application of thermal insulation material on the front door and back wall is necessary. Thick and bulky insulation materials like glass fibre was found to be unsuitable because there is only a few centimeters clearance when the rubber is loaded into the room. The forklift truck may, therefore, easily damage the glass fibre. Thin insulating material which is commercially available appears in the form of liquid coating, e.g., ceramic fiber. However, its application to the inner surface is not possible because the atmosphere inside the room is very corrosive (even the construction bricks do not last long). Economic analysis revealed that the ceramic fiber is feasible but coating must be on the outside surface [4].

The rubber smoking industry is not sensitive to the firewood price. In general, about 10 m^3 of firewood is required for each batch of the smoking. This amount of firewood costs the factory only 1000 Baht (US$ 38) which is insignificant compared to about 700,000 Baht (US$ 27,00) worth of raw material. Heat lost through the back wall and the front door, which is common in every room, was equivalent to about 2.25 m^3 or 225 Baht (US$ 8.6) of firewood. This makes energy saving measures that reduce firewood consumption insufficiently attractive for the factory's owners if there is a better alternative.

At present the smoking process for a batch of rubber sheets takes 5 to 9 days depending on the season (dry or wet). As a matter of fact, it indicates the effect of moisture content of the inlet air. Water removed from the rubber is generally in the range of one ton while water from the inlet air can be estimated at 2-5 tons (depending on season). Furthermore, water inherent in the air uses a huge amount of heat (from combustion) to raise its temperature to the room temperature. This hot vapor does not only possess no beneficial property for the drying process but also causes more firewood to be burnt to maintain the required room temperature. In contrast, if dry air is used in conjunction with dry firewood, the specific wood consumption will be less because there is no extra heat required to vaporize and heat the water. The real advantage appears in the shorter processing time (because of much lower relative humidity in the hot air). Shorter processing time means less wood consumption and a higher production rate.

Low relative humidity in the smoking room is desirable because it can accelerate the drying time. Relative humidity in the room can be reduced by raising the room temperature or dehumidifying the inlet air and using dry firewood. However, the room temperature is limited by the temperature-tolerance property of the rubber. The current practice has already arrived at the maximum allowable temperature of 70°C.

Although the low relative humidity can be achieved by both dehumidification of the inlet air and the use of dry firewood, only the former is practical. Not only is a higher mass of water contributed by the inlet air but also wet (green) firewood is essential as it generates a larger amount of smoke than the dry firewood does. It is then likely that, if it is economically viable, inlet air dehumidification could possibly be a promising technique for the rubber smoking industry as it can significantly increase the productivity by reducing the drying time.

CONCLUSION

From the engineering point of view, there are two parameters to be managed in the rubber smoking process: energy and moisture. Energy use is usually viewed as a serious issue for the factory as it directly affects the production cost. Although only 1/3 of the input energy was used for the smoking process and 2/3 was lost via conduction and ventilation, it was found that energy saving measures are unlikely to be accepted as the benefit is not attractive enough (compared to the benefit from inlet air dehumidification) for the factory's owners to invest in. Reduction of relative humidity in the smoking rooms is desirable as it can significantly increase the productivity and save firewood by shortening the processing time. As half of the water in the process comes from the inlet air, any technique that dehumidifies the inlet air economically deserves serious consideration.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to the Australian Government for financial support through the ASEAN-Australia Energy Cooperation Programme.

REFERENCES

1. Reutaitananond, C. (1991), Security of Thai Rubber Industry and International Cooperation, *Office of Rubber Replanting Aid and Fund News*, 29 (115), pp. 29-34 (in Thai).
2. Prasertsan S., G. Prateepchaikul, N. Coovattanachai, P. Kirirat, S. Nakgul, P. Honghirunrueng and P. Ngamsritragul (1991), Wood Utilization in the Smoked Rubber Industry : Southern Thailand Case Study, *RERIC Int. Energy J.*, Vol.13, No.1, pp. 19-28.
3. Prasertsan S., N. Coovattanachai, P. Kirirat, S. Sen-Ngam and G. Prateepchaikul (1991), Predehumidification of Combustion Air : An Alternative for the Rubber Smoking Industry, A paper presented at the *ASEAN-EC Cogen Workshop*, Medan, Indonesia, 15 p.
4. Thanetvongsakul, M. (1991), *Energy Auditing in a Rubber Smoking Factory*, Res. Rept. No. 15/1/1991, Dept. Mech. Eng., Prince of Songkhla University, Thailand, 157 p. (in Thai).
5. Prasertsan S., P. Singrat and S. Suwanjaras (1991), *Feasibility Study on the Use of Rubber Plantation Wastes for Energy Production*, Final report submitted to STDB, Bangkok, 40 p.
6. Coovattanachai, N., G. Prateepchaikul, P. Ngamsritragul, S. Nakkun and P. Kirirat (1988), Performance of Small Steam Engine Operating on Wood and Rice Husk, *RERIC. Int. Energy J.*, Vol. 11, No. 2, pp. 1-23.
7. Perry, R.H. and D. Green (1984), *Perry's Chemical Engineers' Handbook,* 6th ed. Ch 3, Mc Graw-Hill, NY.
8. Holman, J.P (1981), *Heat Transfer*, 5th ed., Mc Graw-Hill, Auckland, 570 p.
9. Jongkulmanee, A., S. Vichienban and V. Thampramual (1991), *Optimum Condition for Drying of Ribbed Unsmoked Rubber Sheets*, Res. Rept. No. 9/2/1991, Dept. Mech. Eng., Prince of Songkhla University, Thailand, 132 p. (in Thai).

APPENDIX

Equations for Energy Analysis

Symbols and Constants

A = Wall area (m^2)
HV = Heating value of rubber wood = 13,600 kJ/kg [5]
L = Height of door (m)
Q_{in} = Input energy to the smoking room (kJ)
Q_{lc} = Energy loss due to conduction through walls (kJ)
Q_{le} = Exhaust loss (kJ)
Q_{sr}, Q_{sc} = Heat stored in rubber and room structure, respectively (kJ)
Q_{vr} = Latent heat of water (kJ)
T_i, T_o, T_a = Inside, outside wall surfaces and surrounding temperatures, respectively (K)
a = Ash content of rubber wood = 0.041 [4]
$C_{pH_2O}, C_{pv}, C_{pa}$ = Specific heat of water, water vapor and air, respectively.
C_{pr} = Specific heat of rubber = 1.84 kJ/kg K [6]
C_{ps} = Specific heat of room structure materials
$h_{fg\,65°C}$ = Latent heat of water at 65°C
k = Thermal conductivity (W/mK)
m_a = Mass of dry air (kg)
m_r = Mass of smoked rubber (kg)
m_s = Mass of room structure (kg)
m_w = Mass of firewood (kg)
m_{wr} = Mass of water removed from rubber (kg)
t = Time (sec)
x = Wall thickness (m)
ϕ = Wood moisture content = 0.422 wet basis [4]
υ = Kinematic viscosity (m^2/s)
ω_i, ω_e = Humidity ratios of inlet air and exhaust, respectively.

Table: Thermal properties of room structure [6, 7].

Structure Material	k (W/m K)	Cp (kJ/kg K)	Estimated Mass (kg)	Thickness (m)
Brick (left wall)	1.13	0.922	10351	0.075
Brick (right wall)	1.13	0.922	10351	0.075
Brick (back wall)	1.13	0.922	2911	0.075
Gypsum board (ceiling)	–	1.084	562	0.004
Steel (door)	–	0.522	500	0.0012
Concrete (floor)	–	0.653	33221	0.200

Maximum temperatures used in heat storage calculation were obtained from the maximum of the averages of 10 consecutive measurements advancing through the whole range of data. That is, it started with averaging the temperatures of records 1-10, 2-11, 3-12... then used the maximum value of these averages for the calculation.

Input Energy

Calculated from fuelwood heating value

$$Q_{in} = HV.\,m_w(1-\phi) \tag{1}$$

Energy Losses

1. Conduction through walls

$$Q_{lc} = \Sigma\left(kA\,\frac{\Delta T}{\Delta x},\,\Delta t\right) \tag{2}$$

2. Radiation and Convection of Steel Door [7]

Door is made of thin steel sheets. Energy loss is calculated with respect to radiation and convection.

Radiation $$Q = \Sigma\,(\varepsilon\sigma A\,(T_o^4 - T_\alpha^4)\,.\,\Delta t) \tag{3}$$

where,

ε = 0.80
σ = 5.67×10^{-8} (W/m^2 K^4)

Free convection $$Q = \Sigma\,(hA\,(T_o - T_\alpha)\,.\,\Delta t) \tag{4}$$

where,

h = $0.95\,(\Delta T)^{1/3}$ for $Gr_L \Pr > 10^9$, and

$$Gr_L \Pr = \frac{g\beta\left(T_o - T_\alpha\right)}{\overset{2}{\upsilon}}\,L\,.\,\Pr$$

where,

g = 9.81 m/s^2
β = $1/T_\alpha$
υ = 20.76×10^{-6} m^2/s at 350 K
Pr = 0.697 at 350 K

3. Exhaust Loss (with reference to surroundings)

$$Q_{le} = m_{Tg}\, C_{pa}\, \Delta T + m_{Tv}\, C_{pv}\, \Delta T$$

where,

m_{Tg} = Total exhausted gas (kg)
= $m_a + (1-a)(1-\phi)\, m_w$
m_{Tv} = Total exhausted vapor (kg)
= $[m_a + (1.-a)(1-\phi)\, m_w]\, \omega_e$

Thus $$Q_{le} = \{[m_a + (1-a)(1-\phi)\, m_w]\Delta T\ \}\ \{C_{pa} + \omega_e\, C_{pv}\} \qquad (5)$$

4. Latent Heat That Vaporizes Water in Rubber

$$Q_{vr} = m_{wr}\, h_{fg\, 65^{\circ}\mathrm{C}}$$

where,

m_{wr} = $m_{Tv} - \phi\, m_w - \omega_i\, m_a$
= $[m_a + (1-a)(1-\phi)\, m_w]\, \omega_e - \phi\, m_w\, \omega_i m_a$

Thus $$Q_{vr} = \{[m_a + (1-a)(1-\phi)\, m_w]\, \omega_e - \phi\, m_w - \omega_i\, m_a\}\ h_{fg\, 65^{\circ}\mathrm{C}} \qquad (6)$$

5. Heat Stored in Rubber

$$Q_{sr} = m_r\, C_{pr}\, \Delta T + m_{wr} + C_{p\mathrm{H_2O}}\, \Delta T \qquad (7)$$

6. Heat Stored in Room Structure

$$Q_{ss} = \Sigma\, (m_s\, C_{ps}\, \Delta T\,) \qquad (8)$$