Effect of drying strategies on quality of STR 20 block rubbers

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The aim of this research is to investigate the effect of drying strategies on the quality and energy consumption of the STR 20 block rubber. The initial moisture content of fresh samples were in the range of 40-50% dry-basis at the bed depth of 0.25 metres. Three drying strategies were set under varied drying conditions. The results showed that the rubber dried at 130°C with 40 minute drying time, followed by drying at 110°C with 180 minute drying time had better quality and lower specific energy consumption as compared to the other drying conditions. In addition, the experimental results and the data obtained from the mathematical drying model were compared. This showed that the evolution of moisture and temperature profiles, and the specific energy consumption predicted by the mathematical drying model were in good agreement with the experimental data.

Key words: fix-bed dryer, hot air drying, standard Thai rubber, simulation

Introduction

Thailand has been the world's largest rubber producer and exporter with the planting area of about 19,680 km^2. The total annual product is approximately 2.5 million tons valued of 100,000 million baht. The main rubber products have been exported include concentrated latex, ribbed smoke sheet (RSS), air dried sheet (ADS) and standard Thai block rubber (STR). However, RSS (Grade 3) and STR (No.20) are the products of highest market demand as they have been used in the automobile tyre industry. The block rubber is produced from natural rubber under the quality control process and its quality is clearly identified and standardized (Rubber Research Institute, 2002).

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Drying is a principal process in producing block rubber and requires much more energy than other processes, which result in wasting energy and increased investment. There have been very few studies relating natural rubbers and theirs production process development.

Cousin *et al.* (1993) studied the drying of natural crumb rubber. The drying mechanisms were investigated by determining temperature and relative humidity of both the ambient air and the rubber. The results showed that the rubber was dried over 3 different stages. Stage 1, the rubber layers were saturated with water and temperatures of the ambient air and the rubber granules equaled to temperatures of the wet bulb. Stage 2, the constant drying rate had occurred i.e. the temperature, relative humidity of the air and the water content of rubber rapidly decreased. Stage 3, drying rate decreased (falling rate) i.e. much more air was required for drying. Later in 1995, Naon *et al.* reported the drying of natural rubber and developed the mathematical model to predict the feasible conditions for drying. It was found that the drying rates varied with temperature, drying time and relative humidity. The heat transfer coefficient corresponded to the material temperature and the air temperature. Each parameter obtained from the thin layer drying was taken to predict thick layer drying rate using the mathematical model. It indicated that the model results were in good agreement with the experimental results. The final moisture after drying was defined at 0.8 %. The model was also compared to the semiautomatic Trolly dryer used in the industry. It showed that their results were in good agreement when humidity, temperature, relative humidity and drying energy were considered. Suwannawong (2004) investigated the drying kinetic of block rubber STR 20 (Stage 2). The decreasing of moisture content in comparison to the drying time was considered under the constant drying temperature. It was found that the initial moisture content and the hot air temperature had affected the thin layer drying rate. The increased hot air temperature resulted in high drying rate. Tirawanichakul and Tirawanichakul (2005) studied the equilibrium moisture of crumb rubber being used as a raw material for producing block rubber under the constant conditions. The temperatures of 35-60 °C and the humidity ranged from 10-90% were used. Four equations used to determine moisture equilibrium were compared by considering their SSE (sum of squares error) and SD (standard deviation) values. It showed that Halsey’s equation was the most suitable for use in estimation of the moisture equilibrium of the rubber. Desorption of rubber related to the ambient air temperature at the constant relative humidity. In addition, the drying rate depended on the drying time used and the drying temperature.

This research aims to investigate the effect of drying strategies on the quality of STR 20 block rubber using a fixed bed dryer. The quality of block rubber will be compared to the standard criteria of STR 20. The energy consumption of the drying will be studied. In addition, the mathematical model will be established in order to be used to compare with the experimental data as well as to predict the future experimental results.

Apparatus and experimental procedures

Dryer

A demonstration dryer as shown in Fig. 1 was employed in this research; the dryer dimension: 0.35 x 0.70 x 0.80 m (W x L x H). Twelve of 2 kW vane axial heaters and a 2 HP 380 V motor-driven fan were used.

Drying conditions

The initial moisture contents of raw rubber ranged from 40-55% dry basis. The bed depth of raw rubber was set at 0.25 m (approximately 19 - 21 kg weight). The experiments were undertaken at 3 different strategies as follows;

- Strategy I, the rubber was dried at constant temperature ranging from 108 – 130 °C, air flow rate of 2.5 m/s, 220 min drying time, and the air flow was passed through the crumb rubber from the top to the bottom.
- Strategy II, the drying was carried out over 2 stages; stage 1 the rubber was dried at 130 °C with 40 min drying time; and followed by stage 2 dried at 110 °C, 180 min drying time, air flow rate 2.5 m/s, and the air flow was passed through the crumb rubber from the top to the bottom.
- Strategy III, the drying was carried out over 2 stages; stage 1 the rubber was dried at 130 °C with 40 min drying time, air flow rate 1.8-2.5 m/s, and the air flow was passed through the crumb rubber from the top to the bottom.; and followed by stage 2 dried at 110 °C, 180 min drying time, air flow rate 1.8 - 2.5 m/s, and the air flow was passed through the crumb rubber from the bottom to the top.

The temperatures of rubber layers were recorded at the thickness of 0.05, 0.10, 0.15, 0.20, 0.25 m, respectively. The ambient air temperatures and wet bulb temperatures were also checked. The temperatures and rubber weights were recorded every 5 min. The dried rubbers were tested for the compliance with the STR 20 standard. The energy consumption of the drying was recorded.

Measurement Method

- Temperature; using K thermocouples connected to a recorder (Wisco DL-2100, error ±0.1%).
- Moisture content; using the standard method of the Association of Official Agricultural Chemists (AOAC., 2000)
- Rubber quality; using the standard test of block rubber STR 20 by measuring dirt content (% DIRT), ash content (% ASH), volatile material content (% VM), nitrogen content (% N_2), initial plasticity (% PO) and plasticity retention index (% PRI). These parameters were measured at the laboratory of the Southland Resource Co., Ltd.
- Energy consumption; using a Watt – hour meter

Mathematical model of the drying process

This study has modified the mathematical model of a fixed-bed thick layer drying developed by Soponronnarit (1988) and Achariyaviriya *et al*. (2000). The assumptions applied for predicting of block rubber drying are: thermal equilibrium between moist air and rubber has been reached, air flow is a plug-flow type, and there is no temperature gradient existed in the rubber. The mathematical model is developed as the following steps;

1. Calculation of equilibrium moisture content of the rubber

According to the study of equilibrium moisture of crumb rubber by Tirawanichakul and Tirawanichakul (2005), the relative humidity of the rubber is proposed as the following equation:

$$1 - RH = \exp\left(-ATM_{eq}^{B}\right) \quad (1)$$

where
A = 0.00686577
B = 1.02474
RH = relative humidity of the rubber, %
T = temperature of the rubber, °C
M_{eq} = equilibrium moisture content of the rubber, % dry basis

In order to calculate the moisture ratio of the raw rubber, the empirical thin layer drying (two-term exponential) equation (equation 2) and theoretical thin layer drying equation (equation 3) will be employed. Equation 2 had been developed by Sharaf-Elden *et al.* (1980) as shown below:

$$MR = \frac{\left(M_t - M_{eq}\right)}{\left(M_{in} - M_{eq}\right)} = A\exp\left(-Bt\right) + (1 - A)\exp\left(-BAt\right) \quad (2)$$

where $A = -0.000012\mathrm{T}^2 + 0.002507\mathrm{T} + 0.973109$, $R^2 = 0.99$

$B = 0.00049674\mathrm{T}^2 - 0.1016144\mathrm{T} + 5.291145$, $R^2 = 0.99$

MR=Moisture ratio of the rubber, kg water/kg of dry weight

M_t=Moisture content at time t, % dry basis

Subscript

t = drying time, min

eq = condition at the equilibrium

in = condition at the initial time of drying

The diffusion equation (3) for an infinite slap-shaped bed is used for calculating the moisture ratio as follows:

$$MR = (8/\pi^2)\sum_{p=0}^{\infty}[1/(2p+1)^2]\exp[-(2p+1)^2\pi^2 X^2/4] \qquad (3)$$

where $X = A/V(Dt)^{1/2}$

$D = A\exp(\frac{-B}{T_{abs}})$

A=0.000015 , $R^2 = 0.96$

B=113.2885 , $R^2 = 0.96$

2. Calculation of ambient air conditions after drying

By considering the control volume CV1 (Fig. 1), the moisture change of the air is equal to the water content evaporated out from the rubber (mass balance). This can be expressed as the following equation:

$$W_f = (M_{in} - M_f)R + W_{mix} \qquad (4)$$

where $R = \frac{M_{pw}}{m_{mix}\Delta t}$

Regarding to the energy balance, it can be stated that the sum of the enthalpy change of the air and the internal energy of the rubber is equal to the sum of the heat exchanged between the drying system and the ambient air. This can be written as the following equation:

$$T_f = \frac{c_a T_{mix} + W_{mix}(h_{fg} + c_v T_{mix}) + Rc_{pw}\theta - W_f h_{fg}}{c_a + W_f c_v + Rc_{pw}} \qquad (5)$$

where W = Moisture ratio of the air, kg water/kg of dry air

M_{pw} = Dry weight of the rubber, kg

m = Mass flow rate of the dry air, kg/s

R = Dry weight ratio of the rubber and the air

c = Specific heat capacity, kJ/kg °C

T = Temperature, °C

θ = Temperature of the rubber, °C

h_{fg} = Heat of evaporation, kJ/kg

Subscript

f	=	final drying condition
mix	=	Air mixture before entering drying chamber
a	=	Dry air
v	=	Vapor
pw	=	rubber

3. Calculation of temperature of the air mixture and recycle of the air

By considering the control volume CV2 (Fig. 1) as the recycled air chimney, enthalpy change of the air is equal to the sum of the heat exchanged between the recycled air chimney and the ambient air (according to the energy balance). Hence, the temperature of the recycled air (before entering to mix with the ambient air) can be calculated as the following equation;

$$T_{f2} = \frac{Q_2/(RCm_{mix}) + C_a T_f + W_f C_v T_f}{C_a + W_f C_v} \qquad (6)$$

where T_{f2} = Temperature of the recycled air before entering to mix with the ambient air, °C

RC = Recycled air ratio after drying, %

Q_2 = Heat loss rate of the recycled air chimney to the environment, kW

When considering the control volume CV3 (Fig. 1) where the mixing between the recycled air and the ambient air takes place, the vapor content before entering the drying chamber is equal to the sum of the vapor content of the ambient air and the vapor content of the recycled air (according to the mass balance). This can be shown as the equation below:

$$W_{mix} = (1 - RC)W_i + RCW_f \qquad (7)$$

And the rate of enthalpy change of the air is zero as the heat loss resulting from the heat transfer within a given thin layer is assumed negligible (according to the energy balance) as shown in equation (8):

$$\begin{aligned} &m_{mix}C_aT_x + m_{mix}W_{mix}(2502.3 + C_vT_x) - m_iC_a(T_i) - m_iW_i(2502.3 + C_vT_i) \\ &- RCm_{mix}C_aT_{f2} - RCm_{mix}C_aT_{f2} - RCm_{mix}W_f(2502.3 + C_vT_{f2}) = 0 \end{aligned} \qquad (8)$$

where T_{f2} = Temperature of the recycled air before entering to mix with the ambient air, °C

RC = Recycled air ratio after drying, %

Q_2 = Heat loss rate of the recycled air chimney to the environment, kW

W_i = Moisture ratio of the ambient air, kg water/kg dry air

T_X = Temperature of the air before entering the fan, °C

T_i = Temperature of the ambient air, °C

4. Calculation of the increasing temperature of the air generated by fan

By considering the control volume CV4 (Fig. 1), enthalpy change of the air is equal to the work given to the fan assuming that the heat transfer at the control volume is negligible. Hence, the increasing temperature of the air generated by the fan can be calculated as the following equation;

$$\Delta T_{fan} = \frac{P_t}{1000(\rho_a \eta_f)(C_a + C_v W_{mix})} \quad (9)$$

where ΔT_{fan} = Increasing temperature of the air generated by the fan, °C

P_t = Total pressure of the dryer system, Pa

η_f = Efficiency of the fan, %

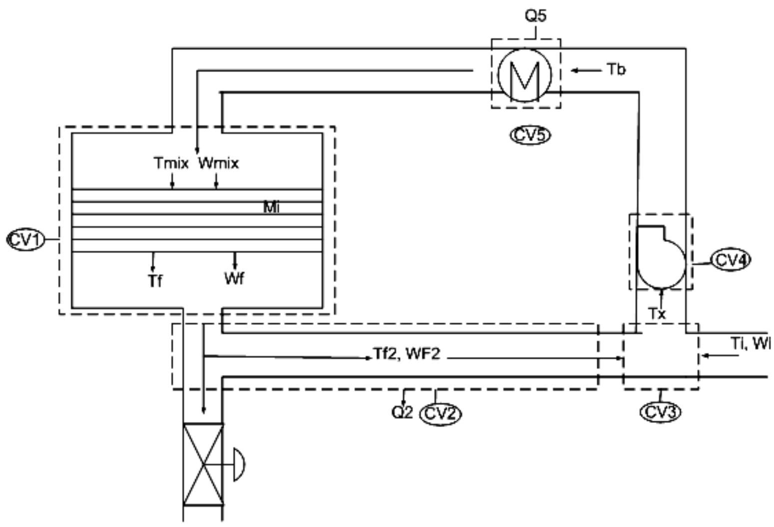


Fig. 1. A demonstration dryer used for STR 20 block rubber drying.

5. Calculation of the energy consumption

By considering the control volume CV5 (Fig. 1), this can be expressed as the following equation;

$$Q_h = [m_{mix}(C_a + C_v W_{mix})T_{mix} - T_b] - Q_5 \int \quad (10)$$

The electrical energy consumption of the fan can be calculated as the equation below:

$$W_M = \frac{P_t\left(m_{mix} / \rho_a\right)}{\eta_f} \quad (11)$$

Hence, the specific energy consumption can be obtained as the following:

$$SEC = \left[\left[2.6\left(\sum W_M\right) + \left(\sum Q_h\right)\right]\Delta t\right] / W_w \quad (12)$$

where SEC = Specific energy consumption, MJ/kg water evaporated
Q_h = Heat energy consumption, kW
W_M = Electrical energy consumption, kW
W_w = Weight of water evaporated out from the rubber, kg

Results and discussions

Evolution of the rubber temperature

The temperature of each rubber layer gradually increased when the drying time increased for every different drying strategy. At approx. 60 min drying time, there were not many differences in the rubber temperatures among each drying strategy which were in the range of 80-95 °C. Strategy I drying results indicated that high drying temperature resulted in more evenly heat distribution in the rubber bed than using lower drying temperature. Strategy II and III which employed high drying temperature in the first stage showed that the temperature of each rubber layer increased rapidly, and approached the same temperature in the second stage that used lower drying temperature. Reversing of the hot air flow in the second stage drying (in Strategy III) resulted in more evenly heat distribution in the rubber bed as shown in Fig. 2.

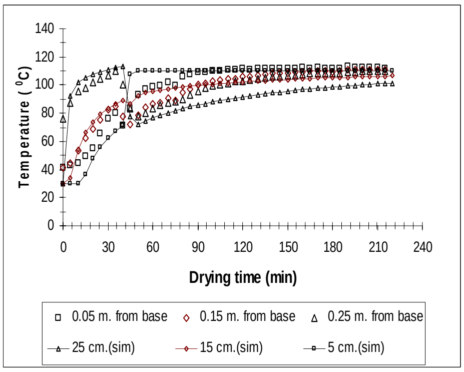


Fig. 2. Evolution of rubber temperatures according to drying time from experimental and simulated results. Conditions: Drying at 130°C for 40 min (air flow: top to bottom, 2.5 m/s) and followed by at 110°C for 180 min (air flow–bottom to top, 2.5 m/s), M_{in} 46.65% dry basis.

Evolution of the rubber moisture content

Strategy I drying results showed that the moisture gradually decreased and became constant. The time taken to decrease the moisture content until it became constant of the high drying temperature was less than when using lower temperature. Strategy II and III using high temperature in the first stage, the results indicated that the moisture content rapidly decreased in the first stage and gradually decreased in the second stage as shown in Fig. 3. This evolution of the moisture content corresponded to that of the rubber temperature.

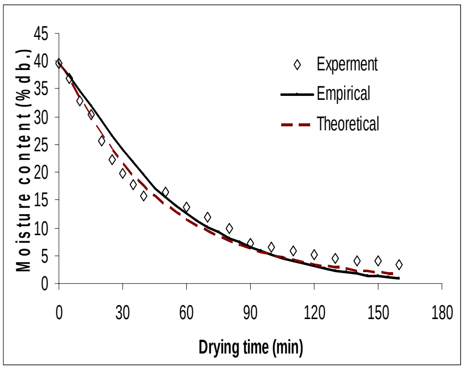


Fig. 3. Evolution of rubber moisture contents according to drying time from experimental and simulated results. Conditions: Drying at 130°C for 40 min (air flow: top to bottom, 2.5 m/s) and followed by at 110°C for 120 min (air flow – bottom to top, 2.5 m/s), M_{in} 39.61% dry basis.

The quality of rubber after drying

Strategy I drying results showed that the dried block rubber appeared to retain a high amount of moisture content and white granules evenly dispersed in its texture when using the low drying temperature. When using higher drying temperature, it was observed that the dried rubber texture still contained a small amount of the white granules at the bottom of the block rubber, and the sticky gel look alike appeared at the top of the rubber. Strategy II drying revealed that the visual characteristics of the dried rubber appeared to have a small number of white granules dispersed at the bottom of the block rubber (at the base of the rubber container) and the sticky gel look alike was observed at the area facing the hot air (at 0.25 m thickness above the base of the rubber container). It clearly indicated that this drying strategy was not suitable to be used to produce a good quality of the block rubber. Strategy III drying results showed good visual characteristics of the block rubber i.e. there was no stick gel and white granules appeared in its texture. Hence, the block rubbers obtained from the Strategy III drying were tested followed as the STR 20 standard criteria and the test results were shown in Table 2. It can be seen from the table that the block rubbers were satisfied compared to all standard criteria. Moreover, the drying time for Strategy III can be reduced to only 160 min, whereas it takes 200 min drying for the Strategy I and II.

Energy consumption of the drying

The energy consumption of the Strategy III drying were taken into account as other drying strategies (Strategy I and II) did not provide a satisfied quality for the STR 20 block rubber industry. In the first drying stage, the specific energy consumed during 40 min drying was compared against the 50 min drying time. In the second drying stage, the specific energy consumed when drying at 105 °C was compared against the 110 °C drying temperature. As expected, it was found that 40 min drying time consumed less energy than 50 min drying time and drying at 105 °C consumed less energy than at 110 °C. In addition, the hot air velocities in the range of 1.8-2.5 m/s were compared and it was observed that using lower air velocities consumed less energy than using higher air velocities as shown in Fig. 4.

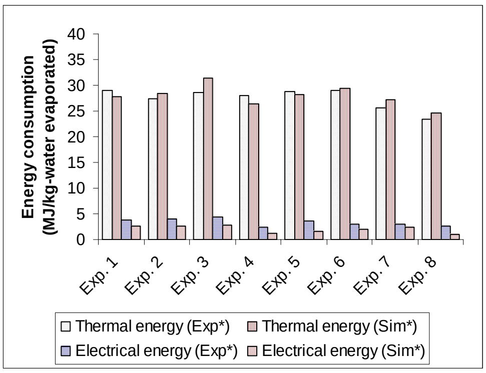
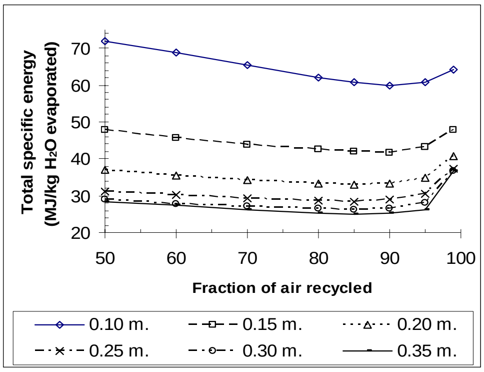


Fig. 4. Comparison of the specific energy consumption from experimental and simulated results.

In conclusion, the Strategy III drying was able to provide good rubber quality followed as the STR 20 standard and consumed the least energy (26.09 MJ/kg-water evaporated). The most feasible drying conditions include drying at 130 °C for 40 min drying time and the air flow was passed through the crumb rubber from the top to the bottom; and followed by drying at 110 °C for 120 min drying time, air flow rate 1.8 m/s, and the air flow was passed through the crumb rubber from the bottom to the top.

Comparison of experimental and simulated results

The comparisons of the experimental and simulated results of the drying were made for the evolution of moisture content and temperature and the specific energy consumption. The conversion factor of kinetic energy or electrical energy converted to heat was used in this study is 2.6. The simulation employed every condition as same as the experimental drying. The simulated parameters include: efficiency of motor, fan, and heater of 0.7, 0.7, and 1.0, respectively; ambient air temperature (30°C), wet bulb temperature (26°C), and recycled air (90%). The mathematical model had been modified from the empirical thin layer drying equation and the theoretical thin layer drying equation. The comparison of experimental and simulated resulted revealed that the temperature evolutions of raw rubber were fairly close at the first layer of the rubber facing the hot air, but relatively different at other layers as can be seen in Fig. 2. Similarly, the moisture content evolutions of raw rubber were fairly close at the beginning of the drying, but slightly different at nearly the end of the drying as shown in Fig. 3. For the specific energy consumption, the simulation agreed reasonably well with the experimental data as displayed in Fig. 4.



Note : Exp* = Experiment, Sim* = Simulation

Fig. 5. Effect of the rubber bed thickness on the specific energy consumption of the drying for a range of bed thickness and fraction of air recycled. Conditions: M_{in} 45 % dry basis, M_f 0.5 % dry basis, air flow 1.8 m/s**.**

Prediction of the drying using the mathematical model

Table 1 compared the experimental and simulated results. It can be seen that the data were relatively agreed. However, the simulation using theoretical thin layer drying equation was taken to predict the drying as it gave better results than those of using empirical thin layer drying equation. The predicted parameters include: ambient air temperature (30°C), wet bulb temperature (26°C), rubber bed thickness (0.10-0.35 m), initial moisture content (30-60%), final moisture content (0.5% dry basis), air flow rate (0.10-0.20 m^3/min-m^3) and recycled air (0-99%). The predicted two-stage drying conditions were drying at 130 °C for 40 min, and followed by drying at 110°C for 120 min. The simulation was used to predict specific energy consumption, moisture content, and rubber temperature at any drying time. The predicted results showed that the specific energy consumption was relatively high when the bed thickness was small (0.10-0.15 m). At the bed thickness more than 0.25-0.35 m, the specific energy consumptions were much lower as shown in Fig. 5. The specific energy consumptions were relatively high when the initial moisture content of the rubber was small (30% dry basis) as can be seen in Fig. 6. Fig. 7 showed that the specific energy consumptions were increased when the air flow rate was higher. The recycled air rate at 85 % resulted in the least specific energy consumption as shown in Fig. 5-7.

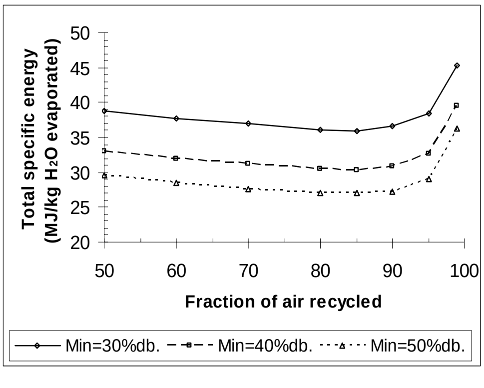


Fig. 6. Effect of initial moisture content of the rubber on the specific energy consumption of the drying for a range of initial moisture content and fraction of air recycled. Conditions: Bed thickness 0.25 m, M_f 0.5 % dry basis, air flow 1.8 m/s.

Conclusions

The block rubbers were dried using the demonstration dryer and the experiments were divided into 3 different drying strategies. The drying simulation model was developed and used to predict the rubber drying. The results can be concluded as follows:-

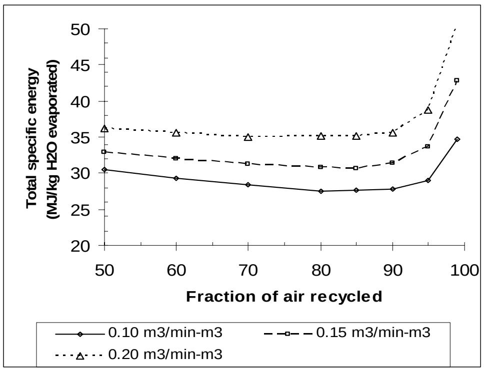


Fig. 7. Effect of the air flow rate on the specific energy consumption of the drying for a range of air flow rate and air fraction of air recycled. Conditions: M_{in} 45 % dry basis, M_f 0.5 % dry basis, bed thickness 0.25 m.

1. Drying under a constant temperature (Strategy I) showed that the temperatures of each rubber layer rapidly increased at the beginning, then gradually reached a constant temperature until the end of drying. High drying temperature resulted in more evenly heat distribution in the rubber bed than using lower drying temperature
2. The moisture content of the rubber rapidly decreased when using high drying temperature but gradually decreased when using lower drying temperature. The initial moisture content had only small effect compared to drying temperature.
3. The two-stage drying with reversing the air flow (Strategy III) produced better quality of the block rubber than other than drying strategies.
4. Drying at 130 °C for 40 min followed by drying at 110 °C for 120 min (air flow rate 1.8 m/s, and the air flow direction was reversed) produced good rubber quality followed as the STR 20 standard and consumed the least energy (26.09 MJ/kg-water evaporated).
5. The simulation model had been established by modifying from two different mathematical drying equations and the simulation predicted the drying process fairly reasonably. However, the simulation using theoretical thin layer drying equation gave better results than those of using empirical thin layer drying equation.

6. The simulation prediction indicated that the rubber bed thickness, the initial moisture content, air flow rate, and the flow rate of the recycled air had significant effects on the specific energy consumption. Decreasing of specific energy consumption was as a result of these drying conditions: high rubber bed thickness and initial moisture content and low air flow rate.

Table 1. Experimental and simulated results of block rubber drying.

Exp. No.	M_{in} %db	Air flow rate (m/s)	Drying air temp. (°C)		Drying time (min)		Thermal Energy consumption (MJ/kg water evaporated)		Electrical Energy consumption (MJ/kg water evaporated)	
			Stage 1	Stage 2	Stage 1	Stage 2	Exp.	Sim.	Exp.	Sim.
1	51.78	2.5	130	110	50	170	29.00	27.78	3.76	2.54
2	46.65	2.5	130	110	40	180	27.43	28.32	4.00	2.57
3	40.85	2.5	130	105	40	180	28.59	31.48	4.35	2.82
4	47.11	1.8	130	110	40	180	28.07	26.45	2.44	1.18
5	43.37	2.0	130	110	40	180	28.87	28.30	3.69	1.60
6	41.95	2.2	130	110	40	180	28.96	29.43	3.08	2.05
7	39.61	2.5	130	110	40	120	25.65	27.18	3.02	2.36
8	44.03	1.8	130	110	40	120	23.48	24.61	2.61	1.02

Note: Exp., Experimental results; Sim., Simulated results

Table 2. Quality test results of the dried block rubbers.

Exp.No.	%Dirt	%Ash	%VM	%N_2	%PO	%PRI
*	≤0.16%	≤0.80%	≤0.80%	≤0.60%	>30%	>40%
1.	0.025	0.40	0.31	0.21	37.0	77
2.	0.019	0.39	0.36	0.34	38.0	76
3.	0.033	0.40	0.36	0.26	39.0	71
4.	0.034	0.37	0.35	0.39	34.5	77
5.	0.032	0.41	0.27	0.33	43	70
6.	0.056	0.38	0.70	0.26	34.5	71
7.	0.033	0.40	0.30	0.33	42.5	69
8.	0.026	0.34	0.45	0.23	42	74

Note: * Standard STR 20 criteria
Exp.1 2-stages: 130ºC 50 min and 110ºC 170 min : Air flow rate = 2.5 m/s
Exp.2 2-stages: 130ºC 40 min and 110ºC 180 min : Air flow rate = 2.5 m/s
Exp.3 2-stages: 130ºC 40 min and 105ºC 180 min : Air flow rate = 2.5 m/s
Exp.4 2-stages: 130ºC 40 min and 110ºC 180 min : Air flow rate = 1.8 m/s
Exp.5 2-stages: 130ºC 40 min and 110ºC 180 min : Air flow rate = 2.0 m/s
Exp.6 2-stages: 130ºC 40 min and 110ºC 180 min : Air flow rate = 2.2 m/s
Exp.7 2-stages: 130ºC 40 min and 110ºC 120 min : Air flow rate = 2.5 m/s
Exp.8 2-stages: 130ºC 40 min and 110ºC 120 min : Air flow rate = 1.8 m/s

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