International Journal of GEOMATE, April, 2020, Vol.18, Issue 68, pp. 120 -128
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2020.68.9186
Special Issue on Science, Engineering and Environment

TWO-STAGE FORCED CONVECTION FURNACE FOR RIBBED RUBBER SMOKED SHEET (RSS) PRODUCTION: PERFORMANCE EVALUATION

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ABSTRACT: Due to improper design of the original rubber smoking-room, Ribbed Rubber Smoked Sheets (RSS) productions at Thai Rubber Smoking Cooperatives (RSCs) are undergoing. In this research, a prototype of the two-stage forced convection system has been proposed to renovate the traditional smoking process. Generally speaking, to enhance the efficiency of fuel consumption and to increase the number of qualitative RSS, the new hot-gas supplying system was carefully designed and constructed. Eight small ventilating lids were specifically used at the smoking-room ceiling to improve the velocity and temperature distributions. To obtain the optimal temperature (60°C) for natural rubber smoking, the feeding rates of firewood and the supplying rates of hot gas while operating this new forced convection system were optimized. According to the RSS production (1458 sheets), the drying time and the fuel consumption were found at 90 hrs., and 1.04 ton per a ton of the dried sheets, respectively. Surprisingly, 92% (822 kg) of the dried RSS were found to be above the selling grades; nevertheless, the remaining was in the cutting-grade due to having the unacceptable thickness (> 3mm). Overall, the new two-stage forced convection system could save 25% of production time and 35% of fuel consumption compared with the original natural convection system. Because the harmful aerosol particles could be trapped, so this new forced convection system may be friendly to the environment as well. In future work, a Computational Fluid Dynamics (CFD) technique will be used to enhance the efficiency of this new smoking-room system for RSS production.

Keywords: Forced convection flow, Natural rubber smoking, Temperature distribution, Energy efficiency enhancement,

1. INTRODUCTION

Thailand has become one of the largest natural rubber (NR) producing and exporting country in the world. In 2018, 3.84 million tons ($1,000 million) of natural rubbers were produced and exported into four forms including Concentrated Latex (36%), Ribbed Smoked Sheet (RSS) (16%), Block Rubber (~1%), and miscellaneous other forms (47%). Due to the price decline of natural rubber, the production of RSS at the community's level has gained more attractive ($2.87 per kg in 2012 to $1.33 US in 2018). Nevertheless, the RSS producing time has taken up to 6 days and the consumed firewood has found as high as 1.5 tons per ton of dried RSS. Over 40 per cent of the produced RSS has been also represented at low quality. As a result, more than half (over 300 groups) of the Rubber Smoking Cooperatives (RSCs) in Thailand cannot be operating. According to the literature reviews, the non-uniformity of the hot gas during the smoking-process has been mentioned and this is because of the improper design of the original smoking-room [1], [2] and [3].

Over a few decades, many researchers have studied the curing parameters for natural rubber drying. For instance, the effects of temperature, velocity, and moisture of inlet air were particularly demonstrated [4], [5], [6] and [7]. In order to lower the RSS production cost, the free and friendly environment energy like a solar house was designed. Basically, the solar heat could be used to preliminarily remove the moisture from the wetted rubber sheets prior to the smoking process [8], [9], [10], and [11]. Furthermore, a recently developed technology like the multiple hot-air jets was particularly suggested for curing the RSS and reducing the production time [12]. As well as, a Computational Fluid Dynamics (CFD) technique was introduced by Promtong and Tekasakul for improving the uniformity of hot gas flow inside the smoking-room. Regarding the recommendations, the original rubber smoking-room was suggested to modify further, then the smoking-time and RSS quality could be significantly improved [1] and [13].

As known, during the burning of the firewood for each RSS production, the harmful wood particles are usually released out to the environment. To protect the worker's health, many researchers have investigated the environmental pollutions at the RSCs. For example, the concentration of the aerosol particles inside the factory area was observed [14], [15], [16], [17], and [18]. Electro Static Precipitator (ESP) was designed to trap a number of particles before entering the smoking-room [19]. As explained, this way could improve not only the RSS quality but also reduce the number of detrimental chemicals released into the atmosphere [20], [21], and [22]. Similarly, the wastewater issue was found to be another critical problem as well [23] and [24]. Therefore, to renovate the current smoking process at the RSCs, the environmental effects should be seriously brought into consideration.

The main objectives of this research are i) to experimentally study the capability of the new forced convection smoking room system under various operating conditions, ii) to investigate temperature distribution inside the modified smoking-room while operates using two proposed functions and iii) to evaluate the performance of the new smoking-room system under real RSS production, especially in term of fuel consumption, production time, and the percent of the RSS satisfied the marketing grades.

2. THE RUBBER SMOKING-ROOM AND ITS MODIFICATIONS

2.1 The Original Smoking Room

The dimensions of the original rubber smoking room are 2.6-wide×6.2-depth×3.7 height-m (Fig.1). On the room floor, twelve 10-cm diameter inlet gas supply ducts are used for hot-air introduction during the smoking period. At the ceiling, two 0.6×0.6-m ventilating lids are installed for the air outlets. Also, there is an 8-m chimney with a 200-mm-diameter used for hot air exhaust and temperature control inside the smoking-room.

2.2 Details of the New Smoking-Room System

Due to having a high-temperature variation inside the traditional rubber smoking room (~15°C), about 40% of the produced RSS were represented at low quality [6]. As a consequence, the parts of the rubber smoking-room were suggested to be modified. For instance, since it was found that a chimney is the cause of the loss of energy, thus the draft tube was disconnected from the heat supply system [5]. However, in this work, the size of the rubber smoking room was not modified because its capacity is suitable for daily RSS production at the community's level.

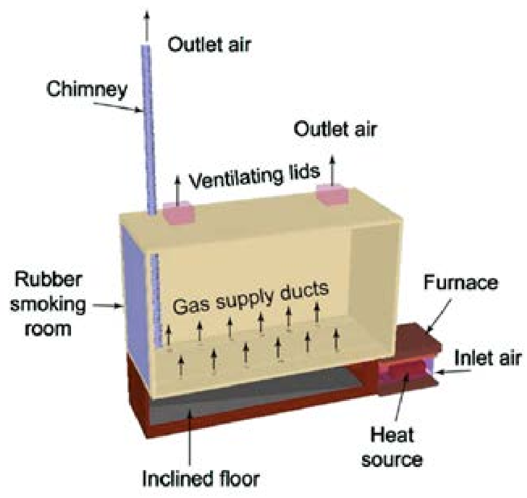

Fig.1 The model of original rubber smoking-room used at Thai Rubber Smoked Cooperatives

2.1.1 *Modifications of the room inlet and outlet*

The adjustment of sizes and positions of the inlets and the outlets of the rubber smoking-room could improve the uniformity of the flow [4]. At the room inlets, 12 round ducts remained the same diameter and positions for the hot gas introduction. However, they are directly connected to the new furnace via the main supply duct (Fig.2). At the outlets, two original ventilating lids (0.6×0.6 m) at the ceiling were replaced by the eight lids of 0.25×0.25 m and their locations are identical with the simulation. Further details can be found in our previous simulation study [1].

2.1.2 *Details of the new two-stage forced convection smoking room system*

The new forced convection system consisting of the heat exchanger unit, a 1-HP-motor with a fan set, and a piping loop, is mainly used for hot gas supplement and circulation (as shown in Fig.2). A Variable-Frequency Drive (VFD) is installed to control the fan speed and torque by varying motor input frequency and voltage. Adjustments of the firewood fed and the motor speed via the VFD, hence the velocity and temperature inside the smoking-room can be controlled within the desired range for RSS production [8].

In practical, this new forced convection system can supply the hot gas to either one or two rubber smoking-rooms. By using two rooms, about 3,150 wetted rubber sheets can be smoked at the same time. For a safety reason, a pressure relief valve is installed at the top of the furnace. Likewise, three dust-trap boxes are installed along the main pipes between the furnace and the smoking-room for blocking and collecting the fly ash (however they are not detailed).

2.1.3 Functions of this new forced convection system

The one-way flowing and the waste gas recirculation are two functions of the new forced convection system that are designed for RSS production. Basically, this first function is proposed to efficiently remove the moisture of the wetted rubber sheets. As shown in Fig.2 the flow path of this one-way supplying mode is started from 1→2→3→4 respectively. Ideally, the desired length of the flow path of hot gas in the smoking-room should be a strength line (as short as possible) from the floor to the ceiling during this function operation. In this first stage, the ventilating lids should be fully opened to allow the moisture flowing out without any blockages.

The waste gas recirculation function is designed to enhance energy efficiency by utilizing the wasted gas. Briefly, the direction of the flow path is started from 5→6→2→3→5, respectively (Fig.2). It should be noted that during this second stage the ventilating lids should be closed so that the wasted gas can be circulated and reused. Therefore, the circulation of the waste gas during this lateral function may reduce the number of soot particles released into the environments.

3. EXPERIMENTAL DESCRIPTIONS

The experiments were carried out using two modified rubber smoking-rooms at Ban-Nong-Deang Samaggi Rubber Cooperative, Nakhon Si Thammarat province, Thailand. Details of tools, measuring positions, research methodology, and performance indicators are described as follows:

3.1 Measurement Tools

Type-K thermocouples were used for the temperature measurement, and a data logger (Data-Taker, DT 500) was used to record the temperatures at 5-min intervals to ensure a continuous reading. A hot-wire anemometer (Airflow, TA400T, 3% full display scale) was used for the velocity measurement. The firewood of known mass was fed to the burner to supply heat to the rubber smoking-room and its moisture content was determined on a dry basis. Drying the wood samples in a laboratory oven at 105°C until its mass did not change, then the moisture content and its heating value can then be examined [25].

3.2 Positions of Measurements

Three positions at the burner inlet were used to measure air velocities. The outlet gas velocities at eight ventilating lids of the rubber smoking-room were also measured for comparison purposes. These measurements were recorded every hour during the

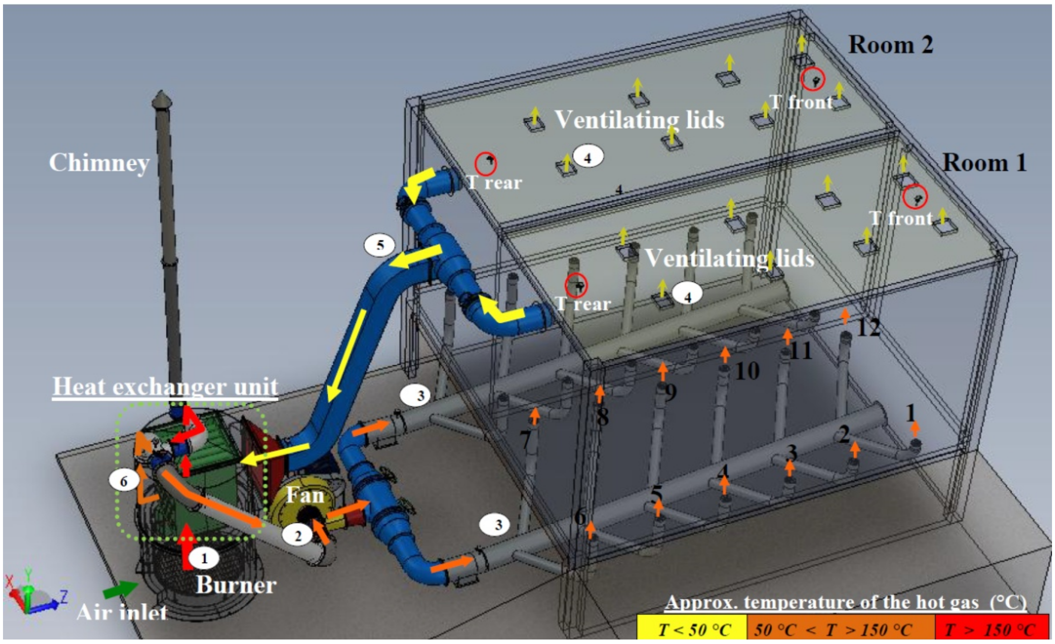

Fig.2 Details of the new smoking-room system and approximate hot gas temperature entering and leaving the smoking-rooms

experimental period and their locations are presented in Fig.3.

Moreover, the temperatures of fifteen positions in the modified rubber smoking-room were also investigated (Fig.3). As well, the temperatures of two positions (T_{rear} and Tf_{ront}) at the ceiling were particularly monitored during the suitable rates of the firewood and the motor speeds were examined. These probe ends are situated at 0.40 m below the ceiling inside the rubber smoking-room (Fig.2). Ambient temperature was also measured, and this measurement was close to the air inlet of the burner.

presented and discussed in the following section.

Thirdly, the new forced convection smoking-room system is used for real RSS production. During the experimental investigations, the fuel consumption, the production time, and the percent of qualitative RSS for the one-room operation are discussed. The performance of this new smoking-room system is then evaluated and reported in this paper. Lastly but most importantly, the instructions regarding how to operate this new forced convection smoking-room system for RSS production are recommended to the RSCs.

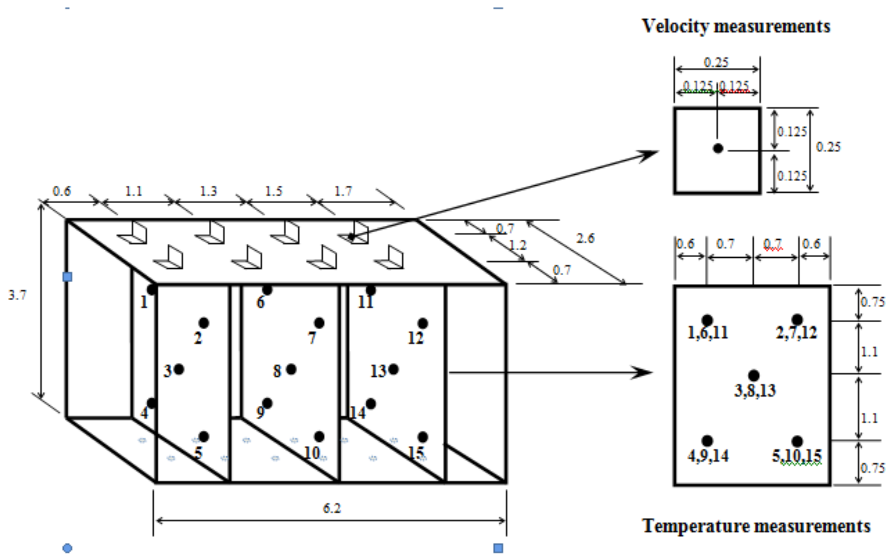

Fig.3 Positions of temperature (side view), and velocity measurements (top view) at the smoking room (units in metres)

3.3 Research Methodology

In order to conduct the experiments for evaluating the capability of the new forced convection smoking room system, this research work is thus divided into four main steps as illustrated in Fig.4. In brief, the fan speeds and the feeding rates of firewood are firstly focused to optimize together with monitors of the temperature occurred inside the rubber smoking-room. To prevent the deterioration of the natural rubber sheet, the smoking temperature is specifically controlled to be around 60°C.

A lower temperature is also acceptable; however, a longer time for RSS production may be required. Temperatures of fifteen positions in the modified rubber smoking-room are secondly investigated under the use of suitable operating conditions. During the experiment, the temperatures were monitored every 5 minutes for continuous reading. The interesting results from this investigation are

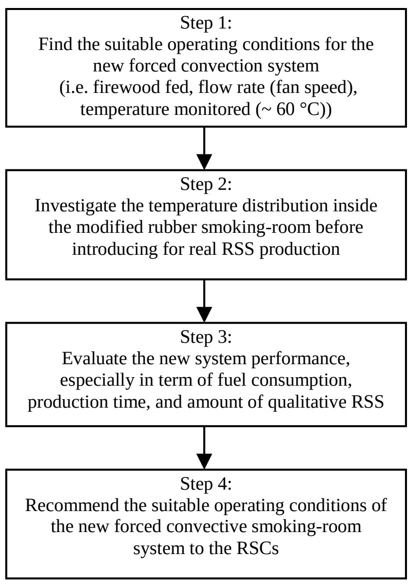

Fig.4 A flow chart representing the main research methodology

3.4 Performance Indicators

Thermal efficiency and specific firewood consumption are normally used for estimating the performance of the new forced convection rubber-smoking system. However, in the section of results, only the specific firewood consumption is discussed. Thermal efficiency ($\eta_{thermal}$) is calculated as shown as follows [26]:

$$\eta_{thermal} = \frac{m_L \times L}{(HV)_{firewood} \times m_{firewood}} \quad (1)$$

where $m_L, m_{firewood}$ are the evaporation mass of water (kg) and the firewood mass (kg), L is the latent heat of vaporization (kJ/kg), $(HV)_{firewood}$ is the heating value of the firewood (kJ/kg).

The specific firewood consumption per ton of dried rubber sheet while using the new smoking room system can be calculated by using the following equation:

$$Firewood - consumption = \frac{m_{firewood}}{m_{dried-RSS}} \quad (2)$$

As mentioned in [27], $m_{dried-RSS}$ is the total mass of dried RSS.

4. RESULTS AND DISCUSSION

The results including the ambient temperature, inlet and outlet velocities (volumetric flow rate), firewood feeding rate as well as temperature variation are firstly presented in this section. To investigate the temperature variation, the experiments were conducted using the empty modified smoking-room, thus the moisture effects can then be ignored. Other interesting results including the ambient temperature, the firewood moisture are additionally given.

After the temperature investigation, this new forced convection smoking-room system was reintroduced for RSS production. So, in the second part of this section, the results regarding the performance indicators of the new smoking-room system, i.e. temperature variation, firewood consumption and percent of satisfied RSS are presented and discussed.

Case 1: Investigating Temperature Variations In The Empty Modified Smoking Room

Because the configurations of the two modified smoking-room are identical, thus only one room was used to conduct the experiment. The appropriate operating conditions from preliminary observations were adopted for this temperature distribution investigation. Generally speaking, the maximum difference of the temperature among fifteen locations for both available functions (one-way flowing and waste gas recirculation) was specifically observed and also compared with the original rubber smoking room.

Feeding rates of firewood and inlet/outlet velocities (volumetric flow rates)

To accelerate the temperature inside the modified smoking-room for the first 2 hrs, 60 kg of the firewood was fed at the furnace and the fan speed was specified by setting VFD at 60 Hz (Table 1). From the measurements, the average air velocity at the burner inlet was found about 2.68 m/s and the average hot gas velocity at the ventilating lid outlets was about 1.02 m/s. After calculations, the volumetric flow rates of inlet air and outlet gas were found to be 0.282 m^3/s and 0.421 m^3/s, respectively.

Table 1 The velocities measuring at furnace inlet and ventilating lids and their volumetric flow rate.

Operating function (Time/VFD frequency/Feeding rate)	INLET	OUTLET
	Average velocity (m/s)	Average velocity (m/s)
	The flow rate of inlet air (m^3/s)	The flow rate of outlet waste gas (m^3/s)
One-way flowing (0-2 hrs /60Hz /60 kg every 2 hrs)	2.68	1.02
	0.282	0.421
One-way flowing (2-14 hrs/ 50Hz/ 40 kg every 3 hrs)	2.16	0.88
	0.227	0.365
One-way flowing (14-32 hrs/ 50Hz / 35 kg every 3 hrs)	2.11	0.85
	0.222	0.349
Waste gas recirculation (32-64 hrs/ 40Hz/ 30 kg every 3 hrs)	-	-

After the heating-up period, 40 kg of the firewood was fed at the burner in every 3 hrs during 2-14 hrs and the VFD frequency was reduced to 50 Hz. Average velocities of air entering the burner and the gas flowing out the ventilating lids were found at 2.17 m/s and 0.88 m/s, respectively. According to the values, the volumetric flow rates were 0.227 m^3/s and 0.365 m^3/s, respectively.

The reductions of the firewood fed and the fan speed were due to a requirement of the temperature control around 60 °C. Lower feeding rate of the firewood (35 kg every 3 hrs) at the burner was attempted for the third period (14-32 hrs). As a result, the volumetric flow rates of inlet air and outlet exhaust gas were found slightly lower than the second period (0.222 m^3/s and 0.349 m^3/s).

For the last period (32-64 hrs), the waste gas recirculation function was introduced instead of the one-way flowing. During the operation, the ventilating lids were shut down and the waste gas temperature was circulated and reheated using the heat exchanger. Also, to maintain temperature around 60 °C, the feeding rate of the firewood required was found at only 30 kg every 3 hrs.

Temperature distribution and other interesting parameters

Fig.5 shows the temperature results measured in the modified smoking-room. Clearly, the temperatures are quickly climbed up and reached 70°C within the first hour. With the selected firewood fed and the fan speed, the room temperature can be raised efficiently. During these two hours, the maximum variation of the temperature was found as high as 6.3°C.

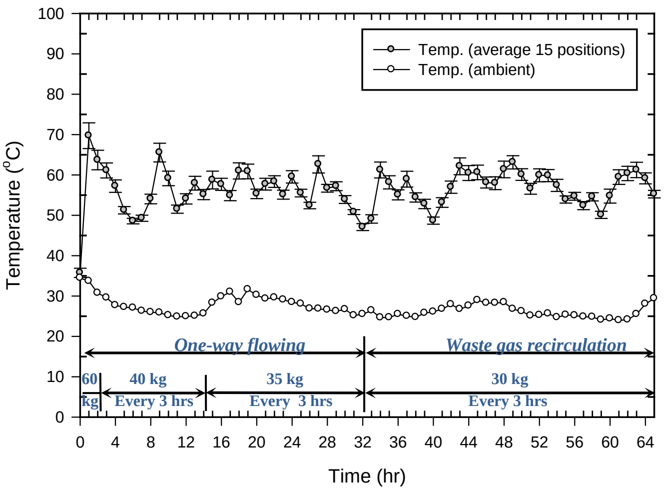

Fig.5 The average temperature of fifteen positions measuring in the smoking-room and the ambient temperature

During the employment of one-way flowing function, all the ventilation lids were fully opened. For the second and third periods (2-32 hrs), the average temperature from the fifteen positions was 56.3°C and the maximum variation remained at 4.6 °C, occurred at a ninth of the experiment.

While the waste gas recirculation (32-64 hrs), the average temperature among the measuring positions was 57.3°C and the maximum variation was reduced to 3.8 °C. According to these results, with a lower feeding rate of the firewood (5 kg every 3 hrs), in general, the average temperature was higher than using the one-way flowing mode.

Using the waste gas recirculation for the last period, the average temperature from fifteen positions was found at 57.3°C, and the maximum variation remained only 3.8°C (Fig.5). The firewood consumption fed in this period was less than that used in the one-way flowing mode about 5 kg every 3 hrs. Nevertheless, it still gave a higher average temperature in the rubber smoking-room.

Because the ambient temperature is usually high and the air humidity is also low during daytimes, hence heating up the room temperature and removing the rubber sheet moisture on this time may be easier and more efficient. According to this reason, the one-way flowing function is suggested to be first introduced during daytimes for RSS production.

Case 2: Evaluating the Performance of the Modified Smoking-Room System for Rss Production

As aforementioned, the performance of the new smoking-room system used for RSS production is another focus to be observed in this work. Prior to the smoking process, the preparations of the wetted ribbed rubber sheets at the RSCs can be reviewed from the work of Dejchanchaiwong [26]. The number of wetted rubber sheets filled up the smoking room for the case of one-room smoking was 1458 sheets. The experiments were begun at 11.00 a.m.; hence the ambient temperature at the beginning was found near the highest on that date.

Feeding rates of firewood and inlet/outlet velocities (volumetric flow rates)

In this experiment, the operating conditions used during the RSS production (0-78 hrs) are similar to the previous study that the temperature variation was investigated. For instance, 60 kg of the firewood feeding rate was fed at the burner for raising the smoking temperature for the first 2hrs (Table 2). Due to an attempt to reduce fuel consumption in the low-moisture period (78-92 hrs), the feeding rate was reduced to 25 kg every 3 hrs.

As shown in Table 2, the velocities of inlet air are between 2.28-2.42 m/s and the average velocities of outlet gas at the ventilating lids are between 0.590-0.644 m/s. The volumetric flow rates of inlet air and outlet gases were at 0.239-0.254 m^3/s and 0.255-0.266 m^3/s, respectively. Also, the velocities and the flow rates measured at the outlets in this RSS production were lower than the previous study about 35%. This may be because the gas had a lower temperature and the rubber sheets also caused the pressure drop.

Table 2 The inlet air velocities, outlet hot gas velocities and their volumetric flow rates

Operating function (Time/VFD frequency/Feeding rate)	INLET	OUTLET
	Average velocity (m/s)	Average Velocity (m/s)
	The flow rate of inlet air (m^3/s)	The flow rate of outlet waste gas (m^3/s)
One-way flowing (0-2 hrs /60Hz /60 kg every 2 hrs)	2.42	0.644
	0.254	0.266
One-way flowing (2-14 hrs/ 50Hz/ 40 kg every 3 hrs)	2.29	0.590
	0.240	0.244
One-way flowing (14-32 hrs/ 50Hz / 35 kg every 3 hrs)	2.28	0.619
	0.239	0.255
Waste gas recirculation (32-92 hrs/ 40Hz/ 30 kg every 3 hrs)	-	-

Temperature distribution and other interesting parameters

The temperatures of fifteen locations measured during the smoking process are presented in Fig.6. As can be seen, for the first 2 hours the temperatures climbed up slowly and reached a maximum of about 55.2°C. During using the one-way flowing function (0–32 hrs), the average temperature was about 52.5 °C and the maximum variation of the temperature was 10 °C.

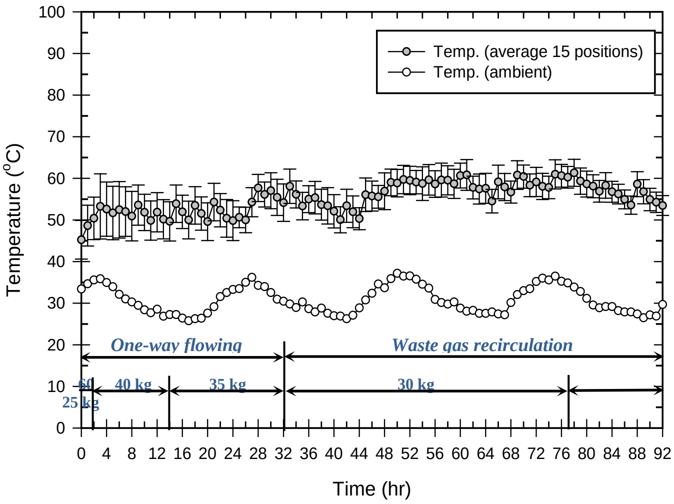

Fig.6 The average temperature of fifteen positions measuring during the smoking process and ambient temperature

The reduction of the average smoking temperature (~8 °C) may be caused by the moisture removal process. During the drying process, the flowing heats were absorbed by the wetted rubber sheets and caused the moisture (mass) transferring to the surface. Afterwards, the moisture was swept away by the carrier gas, as a consequence, the temperature of the hot gas was reduced. Anyways, with a higher rate of firewood fed, the smoking temperature could be increased.

During the waste gas circulation period (32-92 hrs), with the mentioned firewood fed (25-30 kg for every 3 hrs) the average temperature was about 57.1 °C. The maximum variation was found around 8.0 °C, which occurred at the 40th of the experiment (Fig.6). This high variation may be because having a low ambient temperature and high moisture in the smoking room.

5. CONCLUSION

The new two-stage forced convection smoking room system has been proposed to renovate the traditional natural convection smoking-process. To maintain the temperature around the optimal for natural rubber smoking (60 °C), the highest consumption rate was found at 30 kg every 3 hrs. Surprisingly, this consumption rate was less than the average feeding rate used at the RSCs around 35%.

According to the temperature investigation, the maximum difference (4.6 °C) inside the modified smoking-room was found less than approximately three times compared with the original smoking-room. Comparing between the one-way flowing and the waste gas recirculation functions, the maximum temperature variation of the recirculation was found at a lower value (3.8 °C). Also, this temperature result can confirm the previous simulation study.

From the RSS production (1458 sheets), the drying time and the consumption were required at 90 hrs and 1.04 ton per a ton of dried sheets, respectively. After the cutting process, around 822 kg (92%) of the produced RSS represented above the marketing grades. Therefore, it can be anticipated that this new forced convection system could save about 25% of the production time and 35% of the fuel consumption.

6. ACKNOWLEDGMENTS

This research was financially supported by iTAP-Walailak University and the NSTDA, Thailand. Many thanks go to Wood Science and Engineering Research Unit, Walailak University and Mechanical Engineering Department, Prince of Songkla University, for the facilities. Special thanks go to Ban-Nong-Deang Samaggi Rubber Smoking Cooperative and Mr Boonchod Romyen for superb assistance. Many thanks go to Dr Prachid Saramolee, Dr Korakot Suwannarat, Mr Puchong Dangrah, and Mrs Leelanuch Leelapitak for the supports during experimental works.

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