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Design and Performance Testing of Furnace for Rubber Sheet Drying

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ABSTRACT: This article presents the design, construction and performance testing of a biomass furnace used in drying rubber sheet. Indirect heating method is used to make hot air. A small blower is used to run the hot air throughout the drying system. Thus, the proposed drying system is classified as the forced convection type. Shell and tube heat exchanger with multi-pass of flow in tube is employed to increase the heat transfer area. The furnace walls are made of bricks and cement to be the combustion chamber of firewood, packed with the heat exchanger. The experiments are setup to investigate the performance of furnace including average air velocity in the drying chamber, time variation of temperature of air flow in the tube throughout the system and time variation of moisture content in the rubber sheet during drying process.

KEYWORDS: Dryer, Natural rubber, air heating, Biomass

INTRODUCTION

Thailand is the world leader in natural rubber (NR) exports. The total production of the world in 2018 was about 13.9 million tons while Thailand produced 5.1 million tons [1]. 78.8 percent of Thai rubber was exported in the form of block rubber, ribbed smoke sheet (RSS), crepe rubber, concentrated latex and compound rubber. RSS accounted for 12.9% of all products [1]. The Thai government promoted rubber tree planting not only in the south of Thailand but also in other regions such as the north, north-east and east. Currently, 63 provinces of Thailand plant rubber trees with an area of approximately 22 million rai. For this reason, the yield is entered into the market in large quantities, causing the rubber price to fall and affecting many Thai farmers. Most farmers are small farmers with very little productivity. They sold their products in the form of raw rubber sheets, fresh latex, rubber cups and rubber scrapes. In general, farmers sold raw rubber sheets to merchants or smoke factories. Before selling the rubber sheets, they often brought rubber sheets to dry by the sun for ten days. This method was not able to control the quality of rubber such as sticky surfaces, dark color, etc. During the rubber drying process, if there was rain, it would cause the rubber sheet to dry slowly and mold. Other problems of conventional system of RSS production was inequality of dryness in rubber sheets, long drying time and high fuel consumption.

The conventional system of rubber drying was used in Thailand over 30 years [2]. The major heat transfer mode for this direct heating system is the natural convection as shown in Figure 1. The hot air was generated from wood combustion and flow upward past small holes on the floor of drying chamber. This system had simple construction but low thermal efficiency, high fuel consumption, and long drying time. The heat losses occur in several parts including heat loss with the exhaust flue gas flowing out the chimney of oven, heat loss with the hot air flowing out of the rubber drying room through vent, etc. They accounted for 60% of total heat from biomass fuel. The additional shortcoming of this system is the risk to fire disaster because of the small pieces of burning contaminations in hot air [3, 4, 5].

Another means of air heating demonstrated in Figure 2 is the indirect method. Hot air for drying acquires the heat from heat exchanger installed in the biomass furnace. The forced convection is the most important heat transfer mode in this system. The flue gas from combustion process flows in shell side of heat exchanger whereas the air flows in the tube side of heat exchanger. The research papers about heat exchanger design for rubber drying in Thailand have been published since 2011. The direct and indirect systems for rubber drying and smoking were overviewed and compared [6]. Also, the usable energy was pointed out that it is only 25 percentage of fuel energy in conventional oven, direct system. The indirect system was designed and implemented by Wongchang et al. [7, 8] and Matiyanont et al. [9] for large drying room. Their two-pass heat exchangers were extended vertically from the combustion chamber makes the working space of the heating system so large. In contrast to their system, the new six-pass heat exchanger can be packed in the combustion chamber of furnace so the size of heat exchanger is smaller.

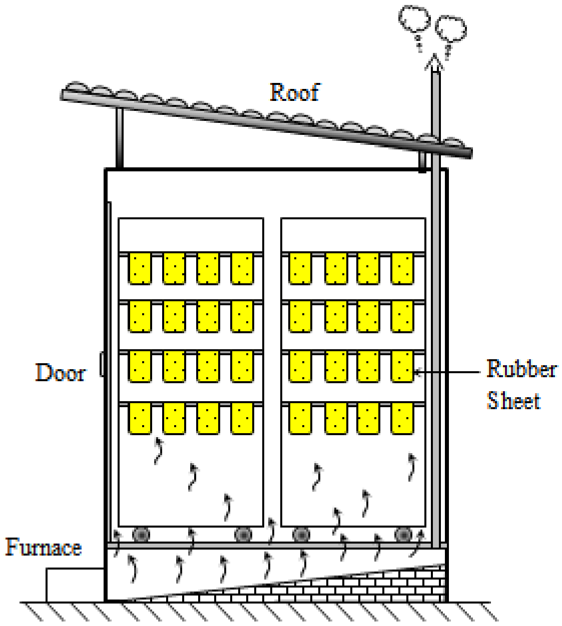


Figure 1. Direct method of air heating for conventional rubber drying room.

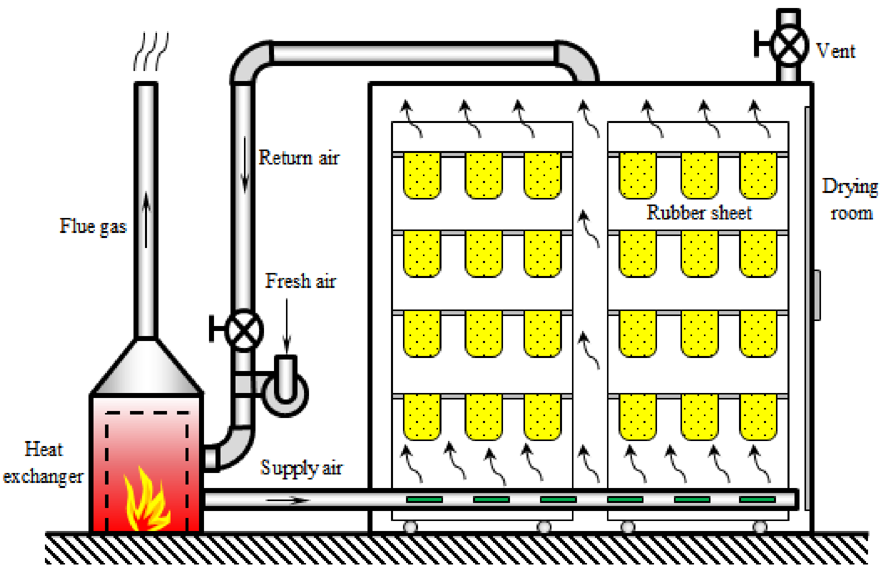


Figure 2. Indirect method of air heating for rubber drying room.

The content of this paper is organized as follows: section 2 describes the theory related to heat exchanger design and information about the oven that was already designed and fabricated, section 3 explains the instrumentation devices, equipment and the procedures for testing the drying system, section 4 reports the experimental results and discussion and section 5 describes the conclusions.

DESIGN

Heat exchanger theory

The most common engineering tools for heat transfer design are Log Mean Temperature Difference (LMTD) method and Effectiveness-NTU method [10].

LMTD of Heat exchanger

The heat exchanger is simplified as the shell and tube which have one shell pass and six tube passes. The hot flue gas from the wood combustion transfers the heat to the cold air that return from the drying room via heat exchanger. The flue gas enters and exits the shell of heat exchanger at $T_{h,in}$ and $T_{h,out}$,respectively. On the other hand, the cool air enters and exits the tube of the heat exchanger at $T_{c,in}$ and $T_{c,out}$, respectively. The Log Mean Temperature Difference (LMTD) can be calculated by

$$\Delta T_{\mathrm{lm}} = F \Delta T_{\mathrm{lm,CF}}, \tag{1}$$

$$\Delta T_{\mathrm{lm,CF}} = \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{\ln\left(\dfrac{T_{h,in} - T_{c,out}}{T_{h,out} - T_{c,in}}\right)} \tag{2}$$

where F is the correction factor which can be estimated from the correction chart [9]. It depends on the temperature ratios P and R given as

$$P = \frac{t_2 - t_1}{T_1 - t_1} \quad \text{and} \quad R = \frac{T_1 - T_2}{t_2 - t_1} \tag{3}$$

where $T_1 = T_{h,in}$, $T_2 = T_{h,out}$, $t_1 = T_{c,in}$ and $t_2 = T_{c,out}$.

The LMTD method is suitable for determining the size and the heat transfer rate of heat exchanger when the mass flow rates, the inlet temperatures and outlet temperatures of the hot and cold fluids are specified. The calculation procedure of this method is simple and easy to use. The LMTD method can be effectively used in heat transfer analysis and design when the fluid inlet temperatures are known and the outlet temperatures are specified or readily determined from the energy balance equation. However, if only the inlet temperatures are known, utilization of LMTD method requires a tedious iterative procedure. Therefore, it is preferable to employ another approach termed the effectiveness-NTU method.

The effectiveness-NTU method

Three important dimensionless parameters called effectiveness (ε), capacity ratio (c) and Number of Transfer Unit (NTU) are defined as

$$\varepsilon = \frac{Q}{Q_{\max}} = \frac{\text{Actual heat transfer rate}}{\text{Maximum possible heat transfer rate}}, \tag{4}$$

$$\mathrm{NTU} = \frac{UA}{C_{\min}} = \frac{UA}{(\dot{m}c_p)_{\min}} \tag{5}$$

$$c = C_{\min} / C_{\max} \tag{6}$$

where $\dot{m}$ is the mass flow rate of fluid, c_p is the specific heat capacity of fluid, $C_{\min} = \min(C_h, C_c)$ and $C_{\max} = \max(C_h, C_c)$ are the minimum heat capacity of hot and cold fluids involved in the heat exchanger, respectively, A is the heat transfer surface area and U is the overall heat transfer coefficient that can be expressed as

$$\frac{1}{U} \approx \frac{1}{h_i} + \frac{1}{h_o} \tag{6}$$

where h_i and h_o the inner and outer heat transfer coefficients of the tube, respectively. This equation is subjected to the assumption that wall thickness of the tube is small and the thermal conductivity of the tube material is high so the thermal resistance of the tube is negligible. The value of 1.6 $W/(m^2 \cdot K)$ for h_o was frequently used for still air. If the inner surface of tube was exposed to 15 mph or 6.67 m/s, h_i was increased to $6\,W/(m^2 \cdot K)$ [11]. The fouling factors on both surfaces of tube are not taken in account. For specified values of U and $C_{\min}$, the value of NTU is a measure of heat transfer surface area A.

The relation of ε and NTU for shell and tube heat exchanger in the case of one shell pass and multiple of two tube passes can be expressed as:

$$\varepsilon = 2\left\{1 + c + \sqrt{1+c^2}\,\frac{1+\exp[-\mathrm{NTU}\sqrt{1+c^2}\,]}{1-\exp[-\mathrm{NTU}\sqrt{1+c^2}\,]}\right\}^{-1} \tag{7}$$

or

$$\mathrm{NTU} = -\frac{1}{\sqrt{1+c^2}}\ln\left(\frac{2/\varepsilon - 1 - c - \sqrt{1+c^2}}{2/\varepsilon - 1 - c + \sqrt{1+c^2}}\right) \tag{8}$$

To estimate the heat transfer surface area of heat exchanger, the effectiveness-NTU method was used in the design step when the outlet temperatures were unknown. The information about the overall heat transfer coefficient from previous studies was also employed in design step [9]. The LMTD method was employed in the verification step by experimental results.

Heat exchanger design

Figure 3 shows a simple diagram of multiple tubes arrangement along four sides of the combustion chamber wall in the two-dimensional view. The front side is the door that allows the air to mix with the biomass fuel in combustion process. The bottom side is the floor of the combustion chamber. The air flows through tubes in multi-pass manner and flue gas flows though shell of heat exchanger only one pass. The left, top, back and right sides of heat exchanger are named as 1, 2, 3 and 4, respectively. In Figure 3, the cold air, the result of mixing of the fresh air and return air, enters to the two tube passes on side 1 and flows into the junction box of the left hand side of side 2. Then, the air enters to the side 3, 4 and exits at the bottom part of side 4. The hot air coming out of the heat exchanger was supplied to the drying chamber by using the centrifugal fan. The heat exchanger was constructed by welding mild steel tubes and sheets.

Figure 4 shows the heat exchanger model and the installed heat exchanger in the furnace. The front panel of junction box can be disassembled and assembled for easily maintenance and installation of twist tape for heat transfer enhancement in the future research. The dimension of heat exchanger is 0.8 m width, 1.51 m length and 1.05 m high. The whole model consists of eight blocks of tube bank. Each block consists of 5 stagger rows of tubes. The total number of tubes in heat exchanger is 184.

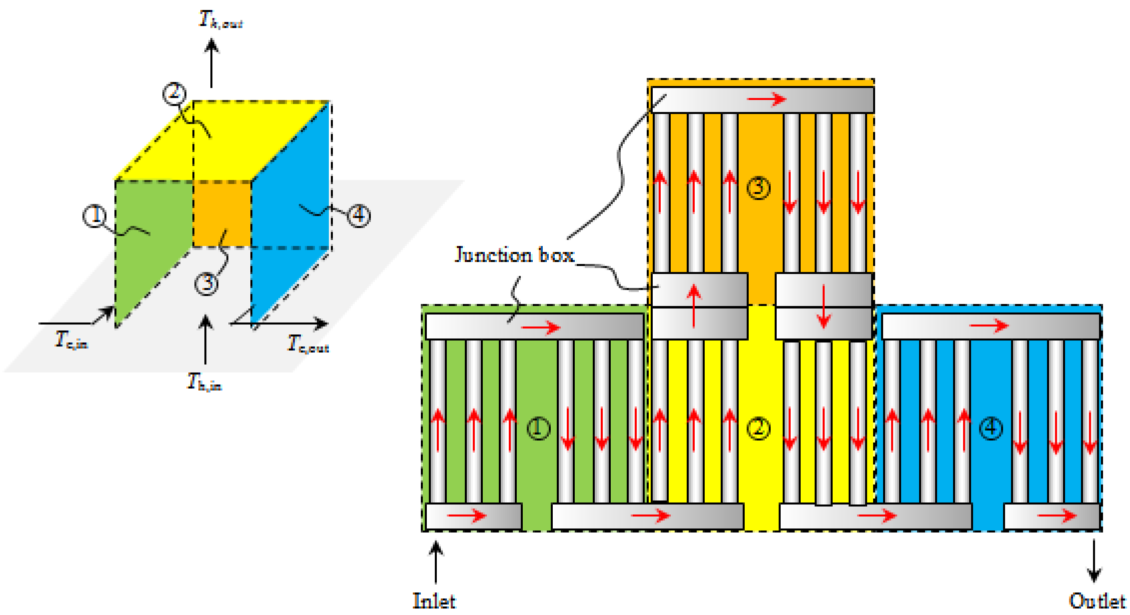
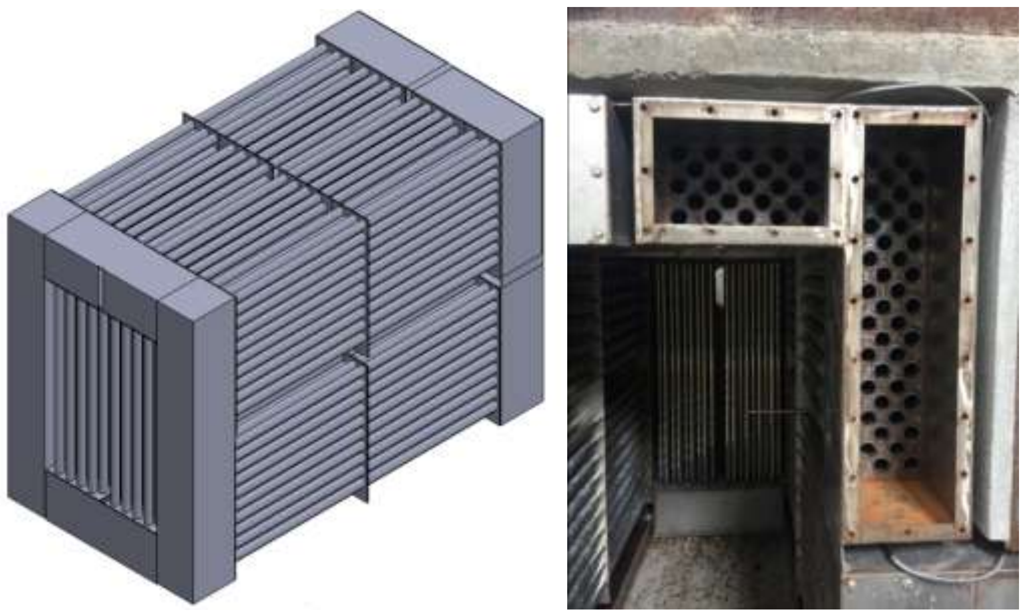


Figure 3. Schematic diagram of the air flow path in multi-tube passes heat exchanger.



(a) (b)

Figure 4. (a) Back side view of heat exchanger model, (b) Installation of heat exchanger in the combustion chamber of biomass furnace.

Biomass furnace was connected with an insulated drying chamber. Table 1 presents some information of heat exchanger and biomass furnace. The maximum number of rubber sheets in drying room is 20. A 370-Watt centrifugal blower was employed to circulate the hot air throughout the system with a fixed air flow rate. The average temperature in drying chamber was controlled by adjusting the feed rate of firewood. The optimum fuel feed rate was found by doing experiments. Normally, the circular pipes were used to connect between components of system. The uniformity of flow distribution in the drying chamber was especially kept by using perforated branch pipes installed at inlet of drying chamber as shown in Figure 5.

Table 1. Information of heat exchanger and biomass furnace

1. Furnace	Fixed grate
2. Fuel	Rubber wood
3. Air heating	Indirect
4. Heat exchanger	One shell pass and six-tube passes
5. Insulation of combustion chamber	Firebrick and fire-protected cement

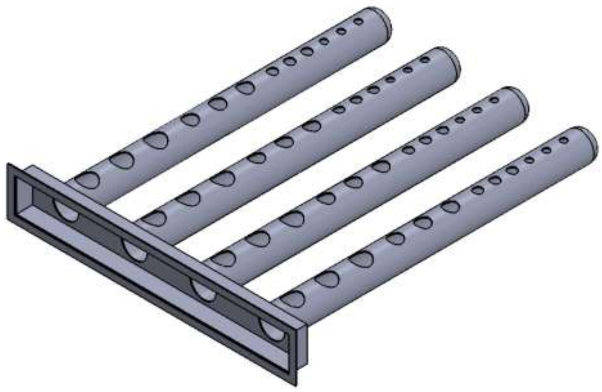


Figure 5. Perforate branch pipes for uniform distribution air flow in drying chamber.

EXPERIMENTAL SETUP

The dryer was designed, constructed and installed at the faculty of engineering, Prince of Songkla University, HatYai, Songkla province, Thailand. The conceptual diagram of dryer is illustrated in Figure 2. The biomass burning furnace integrated with heat exchanger is employed for producing hot air in drying system. The dimension of drying chamber is 1.0m x 1.0m x 1.0m. A part of heat was loss with the air flow to the ambient atmosphere through vents while another one was reused as inlet air of heat exchanger to enhance the energy efficiency of the thermal system.

RESULTS AND DISCUSSION

Temperatures at 6 different positions were measured by type-K thermocouples (0-600ºC) as shown in Figure 6. The temperatures were automatically and continuously recorded every 10 minute as text file in Micro sd-card 8 GB and arduino MEGA 2560 R3 interfacing. The text file can be read from the Microsoft excel. Flame temperature was measured manually by using the infrared thermometer. The ambient air temperature and air temperature at inlet of furnace were measured by digital thermometer. The percentage of removed moisture content from rubber sheet was calculated by

$$M_w = \frac{W_w}{W_t} \times 100 \quad (9)$$

where W_t is the total weight of wet rubber sheet including moisture content and raw rubber, and W_w is the weight of water in wet rubber sheet. The rubber sheet sample was weighted by digital weight balance (SF-400) to determine W_w every hour of drying.

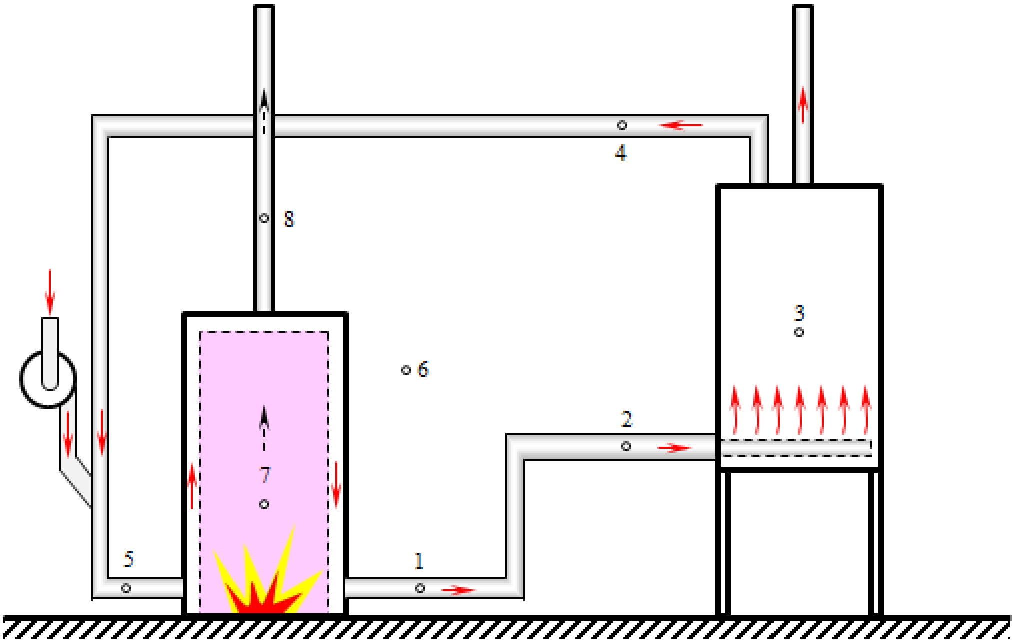


Figure 6. Positions of temperature measurement in drying system

The experiments were divided into three sections. The first experiment was set to measure of air flow rate and air velocity distribution in drying chamber. The second experiment was set to determine suitable heating period for pre-heating the furnace before controlling the temperature of empty drying chamber in the range of 40°C and 60°C. Finally, the third experiment was performed to find the variation of moisture content in rubber sheet.

Air flow rate in drying chamber

The magnitude of local air velocity was measured by using 16-point traverse method for rectangular duct. The turbine meter was employed on the plane area at distance of 10 cm above the base of drying chamber. The magnitude of average velocity on the measured plane is 0.58 ± 0.14 m/s. The perforated branch pipes can effectively control the air velocity inside the drying chamber as unidirectional uniform flow. The air volume flow rate was approximately 35 cmm (cubic meter per minute) across the 1 m^2 area of chamber.

Temperature at various positions in empty drying chamber

The firewood was weighted by dial weighting balance before feeding to the combustion chamber. It is important to assess the appropriate fuel feed rate of the experiments because this parameter was employed to control the temperature in drying chamber. The amount of firewood will be less with continuous air heating as compare to the conventional system. The total time in experiments was approximately 5 hours: 1) one hour for pre-heating the biomass oven and 2) four hours for drying period with controlled temperature. All of experiments were done without using the rubber sheets. The air temperature inside the drying chamber was recommended to be in the range of 40°C to 60°C for the best quality of rubber sheet [12]. Three kilograms of firewood was supplied in the first hour, preheating period, while the 1 kg of firewood was supplied in every subsequence hours. All firewood feedings were done manually. This feeding scheme was the best that we could provide. The temperatures at various positions along the air flow path were shown in Figure 7.

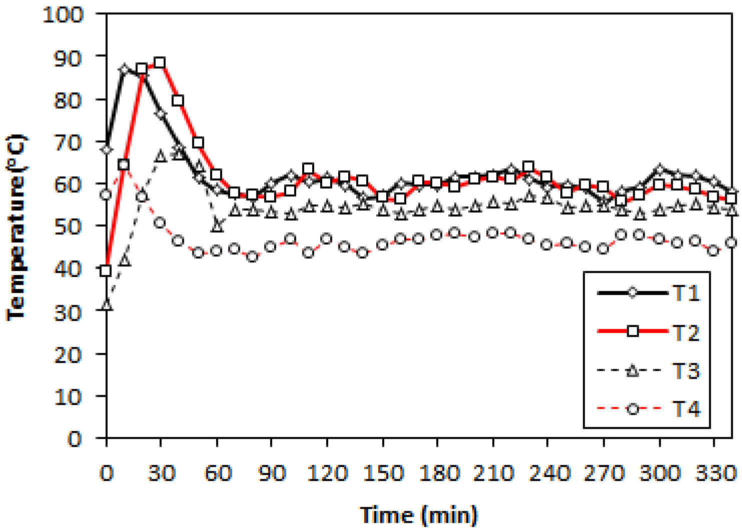


Figure 7. Variation of temperature with time at various positions when firewood feed rate was 3 kg/h in the first hour and 1 kg/h in the subsequent hours.

In Figure 7, one can noticed that the preheating period was about one hour to one and a half hour. A portion of supply heat from firewood accumulated in the structure and other portion of heat transferred to the flowing air. The steady state of temperature in the system occurred when the structure did not accept any heat from firewood. After passing the preheating period, the steady state was observed and the average air temperatures at positions 1, 2, 3 and 4 were 60, 59.3, 54.5 and 46.1°C, respectively. The temperature difference between the inlet and outlet of drying chamber was 13.2°C. The maximum temperature was at the exit of heat exchanger and the minimum temperature was at the inlet of heat exchanger, not shown in Figure 7. The position 3 corresponds to the central position of the drying chamber so its temperature was valid for rubber sheet drying if the firewood scheme was continued.

Figure 8 plotted the variation of flue gas temperature with time. This temperature was measured by infrared thermometer. The large fluctuation of temperature difference between the inlet and outlet of the biomass oven was observed in the first several hours of drying. It can be noticed that the nearly constant temperature difference of flue gas was shown in the last two hours of combustion.

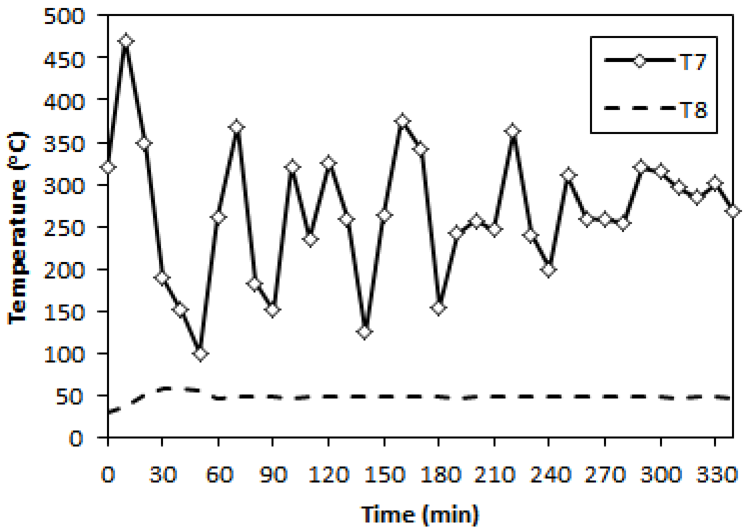


Figure 8. Variation of flue gas temperature with time

Rubber sheet drying

The natural rubber sheet drying experiments were conducted in drying system during April 2019 and purchased from a rubber market in Trung province, Thailand. The dimension of rubber sheet was 50 cm x 90 cm x 0.4 cm. The temperatures at various positions were recorded every ten minutes to ensure that the drying system was operated at appropriate condition. Additionally, the rubber sheet sample was weighted every one hour to evaluate the moisture content that was evaporated by the hot air drying. The results of moisture content were plotted in Figure 9. The reduction of moisture content in the first two hours was nearly negligible. After 3 hours of drying, the moisture content was reduced with constant rate. The drying rate of this test was approximated as 2.93 % wb/hr at the end of the fifth hour.

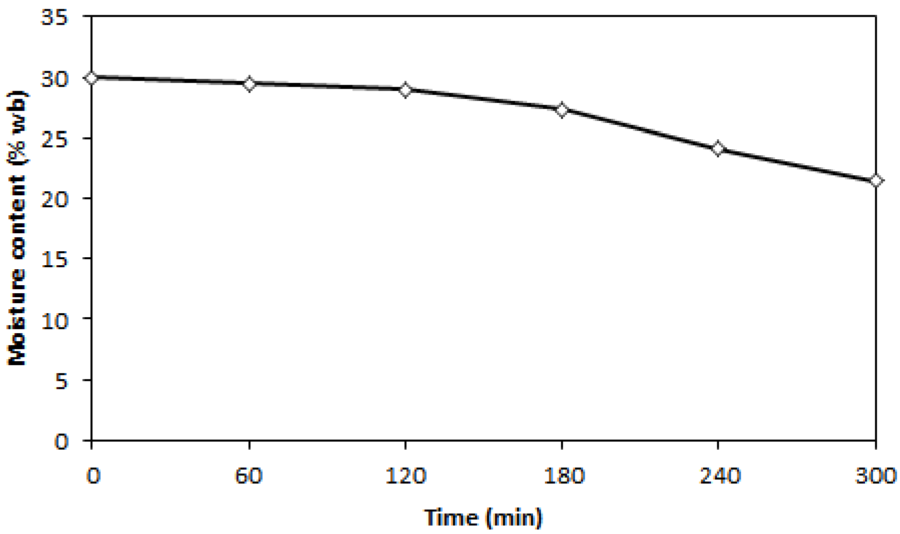


Figure 9. Variation of moisture content in rubber sheet with time

CONCLUSIONS

This paper presents design and development of a biomass furnace for rubber sheet drying. The main components of the drying system are the furnace, heat exchanger, drying chamber and air duct. The heat source of system is biomass combustion in furnace. The heat is transferred to air flowing in the tube of heat exchanger to dry the rubber sheet in the drying chamber. A shell and tube heat exchanger is constructed from steel sheets and tubes, like a cube box in the furnace. The dryer testing involves three parts. Firstly, test for air velocity in the drying chamber. Secondly, test for the best strategy of fuel feed rate for air heating without rubber sheet in drying chamber. Thirdly, test for the moisture content of rubber sheet during drying period.

In term of air velocity in the drying chamber, the air flow rate through the drying chamber was 35 cmm with average velocity of 0.58 m/s. In term of fuel feed rate, the appropriate fuel feed rate of rubber wood was 3 kg/h in the first hour and 1 kg/h in the next hours of experimentation. This scheme of fuel feeding gave the air temperature in drying chamber within 40ºC-60ºC throughout the drying period. However, one hour and a half was reserved for preheating the oven to get the controllable condition in drying chamber. In term of moisture content of rubber sheet, the rate of reduction in moisture content was negligible in the first two hours of drying but its drying rate steadily increased to 2.93% wb/h after the fifth hour of drying.

In the future, the research and development should be continued as follows: (1) combine current dryer with the solar collector for more energy efficient drying method; (2) use the autonomous firewood feeding method into the combustion chamber for less labor dependency; (3) use sensible thermal storage such as brick stack to reduce the operating cost of firewood and increase environmental friendliness [13]; (4) extend the dryer's capability to dry the agricultural products such as mushroom, chili, catfish, etc., and (5) apply the dryer with larger drying chamber for larger productivity of rubber sheet.

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