CONTINUOUS BIOMASS CARBONIZATION SYSTEM USING CHAOTIC MICROWAVE HEATING

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หัวข้อวิทยานิพนธ์	ระบบคาร์บอนไนเซชันชีวมวลแบบต่อเนื่องโดยการให้ความร้อนด้วยไมโครเวฟแบบใช้สัญญาณอลวน
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บทคัดย่อ

ดุษฎีนิพนธ์ฉบับนี้นำเสนอวิธีการใหม่ในการออกแบบและการสร้างระบบคาร์บอนไนเซชันชีวมวลแบบต่อเนื่องโดยการให้ความร้อนด้วยไมโครเวฟความถี่ 2.45 จิกะเฮิรตซ์ แบบหลายช่องทางด้วยวิธีสร้างกระสวนอลวน ซึ่งกำลังสูงสุดในการกระจายความร้อนเท่ากับ 8.5 กิโลวัตต์ ในเตาปฏิกรณ์ซิเมนต์รูปทรงกระบอก ขนาดปริมาตร 0.847 ลูกบาศก์เมตร โดยใช้กะลามะพร้าวเป็นวัตถุดิบชีวมวลในการทดลอง ซึ่งมีอัตราการป้อน 350 กิโลกรัมต่อชั่วโมง ถ่านและน้ำส้มควันไม้อันเป็นผลที่ได้จากระบบจะถูกนำไปวิเคราะห์คุณสมบัติ ส่วนก๊าซเชื้อเพลิงที่ได้จากระบบจะนำไปใช้เป็นเชื้อเพลิงของเครื่องยนต์กำเนิดไฟฟ้า จากผลการทดลองแสดงให้เห็นว่าวิธีการใหม่ที่นำเสนอในงานวิจัยนี้ จะช่วยลดเวลาในการผลิต และสามารถความคุมอุณหภูมิได้ง่าย ผลผลิตที่ได้จากระบบมีคุณภาพสูง

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ABSTRACT

This dissertation deals with a novel design and the fabrication of biomass carbonization system using microwave heating. The heating system employs multi-feed microwave generators with 8.5 kW maximum power and 2.45 GHz frequency for uniform heating distribution inside a 0.847 m^3 cylindrical low cement castable reactor. The new design uses chaotic signals for the microwave feeding pattern. The experiment entailed the carbonization of 350 kg/h of coconut shells, after which the charcoal and wood vinegar yields were analyzed while uncondensed gases were treated to fuel the engine-generator system. The experimental results show that the proposed system can produce high quality product yields at a significantly reduced production time while allowing for ease of temperature control.

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Chapter 1

Introduction

1.1 Introduction

As the demand for energy from fossil fuels by industries has risen and will be more in the future, more burdens have been put on the environment, one of which that is a cause for concern is the subsequent accumulation of carbon dioxide in the atmosphere and thereby rising global temperatures. As a result, many attempts have been made to use biomass as an alternative source of energy to reduce carbon dioxide emission into the atmosphere [1].

A leading agricultural country with numerous kinds of biomass, Thailand produces approximately 61 million tons of biomass waste annually. However, the Kingdom has hardly utilized biomass waste for the production of bio-fuel. Most biomass waste from the agriculture industry was incinerated while that from agricultural activities was either left in the fields/plantations or burned [2]. It was estimated that Thailand could produce from available biomass over 20 million tons of crude oil, which was more than half of the current oil consumption of the country. Consequently, greater utilization of biomass waste should be promoted either by adding value or by transforming into fuels or energy. In addition, the development of biomass conversion technology suitable for biomass resources of different areas would economically benefit both the local community and the whole nation in the long run [3].

The carbonization process is normally employed to convert agricultural biomass waste into biofuels, i.e., solid (charcoal), liquids (bio-liquid, wood vinegar, pyroligneous acid), and fuelgas [4,5]. Charcoal can be made into charcoal briquettes[6]; or induced to obtain activated carbon[7, 8, 9]; wood vinegar can be used as a substitute for the chemical pesticides[10]; and fuelgas as a fuel in internal combustion engines or in electricity production[11]. Therefore, the processed biomass waste and/or agricultural waste to add value would benefit the economy, society, and environment[12]. In addition, the use of biomass waste materials from agriculture could be an answer to the quest for a sustainable source of renewable energy.

The carbonization process of biomass waste from agriculture is a suitable, cost-effective technology for charcoal production in Thailand because the process adds value to the biomass raw materials which are inexpensive and ubiquitous. Furthermore, the process is effective in solving the problem of unwanted biomass waste from agriculture and can be suitably and economically employed by villagers in remote areas to produce electricity for local consumption.

There exist many technologies to produce charcoal from biomass. Also, a number of countries, such as European countries, Australia, the United States of America and Brazil [13], not merely promote the utilization of biomass to produce energy but also encourage the use of energy from biomass. The carbonization process (i.e., charcoal production) has evolved since its inception hundreds of years ago to include multiple loads, new designs, etc. The current carbonization processes can be categorized into two types: batch (e.g., pits, earth mound, brick and metal kilns) and continuous (e.g., drum type pyrolysers, screw type pyrolysers, and rotary kilns) [14]. The current charcoal production methods nevertheless are hardly different from the traditional methods.

Both production types are plagued with many problems including energy wastage for both types of production, time loss and environmental unfriendliness of the batch process, all of which hinder the industrialization of carbonization [5, 14]. In both processes, the conventional heating method is employed whereby the exterior of the reactors is heated and then heat is transferred to biomass inside. The heat transforms the biomass inside the reactors into biofuels, depending upon the size of the biomass and process conditions (i.e., temperature, heating rate and residence time). Unlike the conventional heating method, the alternative efficient heating method, or microwave heating, causes the heat to originate from inside of materials and migrate outward. Research studies on the thermochemical process of biomass with the application of microwave heating have been reported and the research results suggest that this heating method is suited to distributed conversion of large biomass particles [15-21].

The microwave carbonization of biomass is one of the novel thermochemical technologies whereby biomass is irradiated with microwave. The microwave carbonization process offers several advantages over the traditional carbonization process, some of which include uniform internal heating of large biomass particles, ease of control, and saving of time and heat energy. As such, the microwave carbonization is therefore adopted by industries.

The problems with microwave heating systems are the non-uniform heating on loads or workplaces caused by the uneven distribution of electromagnetic inside the microwave cavity. The unevenness of electromagnetic distribution results in hot spots, cold spots, thermal runaway panorama and low product yield quality.

This thesis presents the design of a pilot-scale continuous biomass carbonization system using multi-feed microwave heating. The chaotic pattern signals are used to control radiation from each microwave source to create the uniform heating distribution inside the carbonization reactor. The technique gives the products of high quality.

1.2 Hypothesis of this study

The biomass carbonization process using microwave heating could be an effective solution to the unwanted biomass waste problem and it requires low energy consumption. Review of literature reveals that the main problem with microwave heating is the non-uniform heating distribution inside the reactor. Although this problem can be resolved with turn or conveyer and/or mode stirrer design, it is too complicated. As such, the multi-feed microwave heating using the chaotic signal patterns is employed.

This dissertation uses the principles and basic theories of both microwave and biomass carbonization to form the research concept for design and fabrication of the carbonization system that could process biomass into fuels on an industrial scale.

1.3 Objective

The objectives of this research are as follows:

To develop a pilot-scale continuous carbonization system of biomass using microwave heating technology, which is able to produce 50 kg/hour of charcoal, 15 liters/hour of wood vinegar, and 10 kW/hour of electricity with uncondensed gases.

To apply the multi-feed microwave radiation to heat the biomass inside the reactor of the continuous carbonization system.

1.4 Scope of study

The scope of this study is to design and fabricate the continuous carbonization system using the multi-feed microwave heating to transform biomass to marketable fuels.

1.5 Thesis outline

The organization of this thesis is as follows: Chapter 2 reviews the basic theories of biomass carbonization process and microwave heating. Chapter 3 details design of the continuous biomass carbonization system using multi-feed microwave heating. The fabrication of the system is addressed in Chapter 4. Experiments and results are presented in Chapter 5 while the conclusion is provided in Chapter 6.

Chapter 2

Basic Theory

This chapter briefly reviews the principle of biomass carbonization process and basic theory of microwave heating.

2.1 Biomass carbonization

Biomass carbonization is a process to decompose biomass with heat in the absence of oxygen and is divided into 4 stages: First, biomass is heated to 180 °C, the temperature at which moisture inside the spaces between cells (free water) and at cell boundary (bound water) is completely transformed into non-pungent, non-harmful, pale blue vapor. Second, volatiles are removed by heating the biomass at the temperature range of 180 - 280 °C, and once the temperature reaches 280°C, hemicelluloses are fully decomposed. The temperature is maintained at 280°C for an extended period of time for an optimal carbonization process whereby the heat is evenly distributed to the whole biomass inside the reactor. The yield from this stage is of pale gray color consisting of CO, CO_2, acetic acid, and methanol, all of which are nevertheless of low quantity to be of use. Third, the derived biomass is then converted into charcoal. The temperature range at this stage is approximately 280 - 400°C, the range at which biomass self-decomposes through the exothermic reaction. Celluloses in the biomass rapidly decompose at 280°C and their yield is of white and yellow colors with pungent smell and gives high quality wood vinegar if condensed. Then, lignin decomposes at approximate temperatures of 310 – 400 °C. Beyond 400 °C biomass is entirely converted into charcoal. Finally, charcoal quality is improved in this final stage with removal of tar. Although biomass becomes charcoal after approximately 400 °C, high quantity of tar remains. Tar causes the charcoal to be of low quality and, once burned, changes into benzopyrene and dibenzanthracene, both of which are carcinogenic. Therefore, charcoal is dried at 500 - 600°C for a period of time to remove tar [4]. The product yields from the biomass carbonization system is presented in Figure 2.1.

Fig. 2.1. Product yields from the biomass carbonization system.

2.1.1 Biomass carbonization modeling

A scheme of biomass carbonization process model is presented in Figure 2.2. The biomass (the coconut shell) characterized by its mass flow $\dot{m}_B$ at temperature T_0 enters the chipper, eventually is risen at temperature T_1 by a dryer unit, and hence enters the reactor where the reaction is as at temperature T. The gas leaves the reactor from the top and is chilled giving a flow of bio-oil u_{2l} collected in wood vinegar tank, and uncondensed gas u_{2g} collected in the fuel gas tank. From the bottom of the reactor is collected the charcoal flow u_1. The total mass of charcoal is m_c. The total mass of charcoal is m_g. The amount of gas $k_1 m_g$ and $k_3 m_g$ are changed to electrical power for the reactor heating and the drying process, respectively. The reaction is assumed adiabatic [22].

The heath powers are: H_c, for the char, H_g for the gas; c_p and c_v are the specific heath at constant pression, and at constant volume, respectively. The total mass in the reactor is denoted by M.

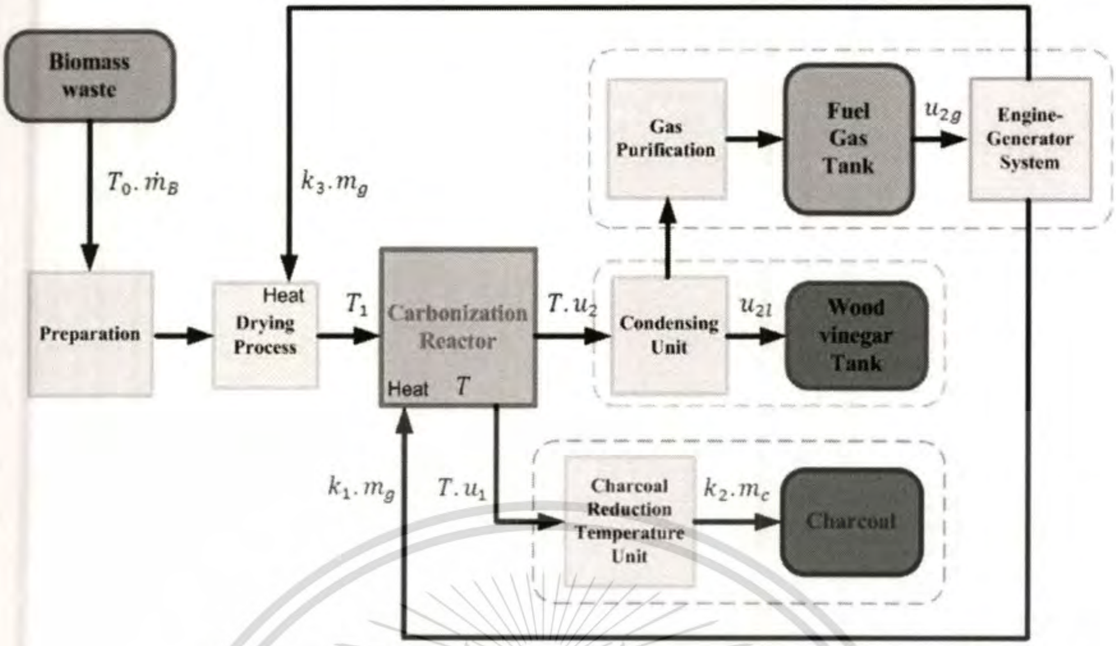


Fig. 2.2. A scheme of biomass carbonization process model.

The biomass carbonization process modeling is shown in Figure 2.2 Assumming the reactor is operating in the range of temperature (450°C, 550°C), we can be described by the following equations:

$$u_1 = \dot{m}_{ci} = \dot{m}_B(-AT + B) \tag{2.1}$$

$$u_{2g} = \dot{m}_{gi} = \dot{m}_B(CT + D) \tag{2.2}$$

, by A, B, C, D are constant value from the technical data.

The balance of energy inside the reactor, By taking into account the heath exchanged into the drier $k_3.m_g.H_g,$ allows the computation of the biomass temperature T_1 at the output of the drier unit T_1:

$$T_1 = \frac{k_3 m_g H_g}{\dot{m}_B C_p} + T_0 \tag{2.3}$$

The balance of energy inside the reactor leads to:

$$\dot{T} = \frac{\dot{m}_B C_p}{MC_v} T + \frac{k_1 H_c}{MC_v} m_c + \frac{k_3 m_g}{MC_v} m_g + \frac{T_0 C_p}{MC_v} \dot{m}_B + \frac{losses}{MC_v} \tag{2.4}$$

The mass flow balance of char and of gas gives:

$$\dot{m}_c = (-A\dot{m}_B T) - k_2\, m_c + B\dot{m}_B \tag{2.5}$$

$$\dot{m}_g = C\dot{m}_B T - k_2\, m_c - D\dot{m}_B\, \dot{m}_B \tag{2.6}$$

At the steady state

$$0 = \frac{\dot{m}_B C_p}{M C_v} T + \frac{k_1 H_g}{M C_v}\, m_g + \frac{T_1\, m_g}{M C_v}\, m_g + \frac{T_0 C_p}{M C_v}\, \dot{m}_B \tag{2.7}$$

$$0 = (-A\dot{m}_B T) - k_2\, m_c + B\dot{m}_B \tag{2.8}$$

$$0 = C\dot{m}_B T - k_2\, m_c - D\dot{m}_B \tag{2.9}$$

In a first instance we may neglect the losses (k_4 =0) and

$$u = \frac{k_1 H_g}{M C_v}\, m_g + \frac{k_3 m_g}{M C_v}\, m_g + \frac{T_0 C_p}{M C_v}\, \dot{m}_B \tag{2.10}$$

As a global control to be used for regulating the temperature T.

2.2 Fundamentals of Electromagnetic and Microwave heating

2.2.1 Maxwell's Equations

This thesis has considered certain cases of interactions between electric and magnetic fields. Maxwell explained these relationships with his famous Maxwell's equations [23]. The relation of electrical phenomena is summarized by Maxwell's equations:

$$\mathrm{div\,D} = 0 \tag{2.11}$$

$$\mathrm{div\,B} = 0 \tag{2.12}$$

$$\mathrm{curl\,E} = -j\omega B \tag{2.13}$$

$$\mathrm{curl\,H} = \mathrm{J} + j\omega D \tag{2.14}$$

with the auxiliary equations

$$\mathrm{J} = \sigma \mathrm{E} \tag{2.15}$$

$$\mathrm{D} = \varepsilon_0 \, \varepsilon \, \mathrm{E} \tag{2.16}$$

$$\mathrm{B} = \mu_0 \, \mu \, \mathrm{H} \tag{2.17}$$

The differential equations can be solved for particular configurations of simple geometry for the boundaries of the fields.

2.2.2 Plane waves

The propagation of electromagnetic waves as plane waves in free space is the simple solution of the Maxwell's equations. The plane wave has only E_x and H_y components that are transverse to the direction of propagation, as shown in Figure 2.3.

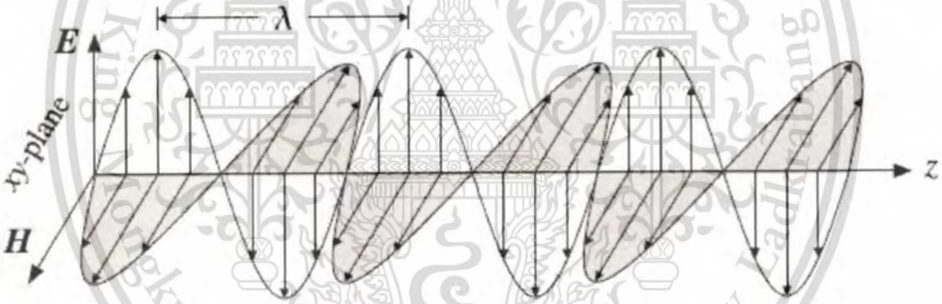


Fig. 2.3. Plane wave.

The plane wave is represented by:

$$E_y = E_0 \sin(\omega t - \beta z) \tag{2.18}$$

$$H_x = \frac{E_0}{Z_0} \sin(\omega t - \beta z) \tag{2.19}$$

where E_0 is an amplitude factor, and

$$Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} \tag{2.20}$$

Z_0 is the characteristic impedance

$$\beta = \frac{2\pi}{\lambda_0} \tag{2.21}$$

, β is the propagation constant.

The power flow associated with a plane wave is E (V/m) x H (A/m). Dimensionally, this gives the power flow as a power flux density P (W/m^2). The electric and magnetic field vectors in plane wave lie in a plane normal to the direction of propagation travel of the wave, and obviously the power flow must also be in the direction of travel, i.e. the Poynting vector, P,

$$P = \bar{E} \times \bar{H} \tag{2.22}$$

2.2.3 Waveguides

A waveguide is a metal tube of rectangular or circular cross section made of copper, aluminum, or brass of various sizes. The waves that propagate inside a waveguide are different from those in free space. TE waves have E_z = 0 while TM waves have H_z = 0. For TE waves, there is a component of H that follows the direction of propagation while for TM waves, it is the E component that exists in the same direction. In both cases, energy is carried by the electric and magnetic fields. The wave forms inside the waveguide have a mode. In waveguide, it has many modes of propagation.

2.2.4 Waveguide frequency cutoff

A cutoff frequency is a minimum frequency below which a given waveguide cannot transmit waves. A waveguide has a cutoff frequency for each allowed mode. If the frequency of the excited mode is above the cutoff frequency, the electromagnetic energy will be transmitted down the guide with little attenuation.

The cutoff frequency, f_c , is given by

$$f_c = \frac{1}{2\pi\sqrt{\mu_0\varepsilon_0\varepsilon}}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2} \tag{2.23}$$

where a and b are the dimensions of the waveguide, and m and n are the mode indices.

2.2.5 Microwave heating

Microwaves are used for their ability to heat materials, which is based on the ability of materials to absorb electromagnetic energy. In industrial application, microwave heating is performed at a frequency between 900 MHz and 2,450 MHz.

2.2.6 Dielectric properties of material

The loss tangent, $\tan\delta$, represents the efficiency of the material to convert absorbed into heat and is used commonly to describe the dielectric response [24].

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \tag{2.24}$$

The angle δ is the phase difference between the oscillating electric field and the polarization of the material.

The permittivity, ε', also known as the dielectric constant, describes the response of a dielectric material to an electric field and is determined by the ability of a material to polarize in response to the applied electric field. In microwave heating, knowledge of the dielectric properties is crucial in determining the response of the material to microwave. In the heating of dielectric materials, it is assumed that the magnetic field does not contribute to microwave absorption, and heating occurs entirely due to the electric field. Where ε' refers to the dielectric loss factor, representing the ability of material to store energy.

The dielectric properties vary with temperature and frequency. Figure 2.4 [25] shows the variation in dielectric properties of water at different frequencies and temperatures. Figure 2.5 shows the dielectric properties of wood (density = 500 kg m^{-3}) as a function of frequency and moisture content varying between 0 % and 100 % on a dry wood basis [25]. In addition, the dielectric properties of the material are also affected by many other factors, such as purity, chemical state and manufacturing process.

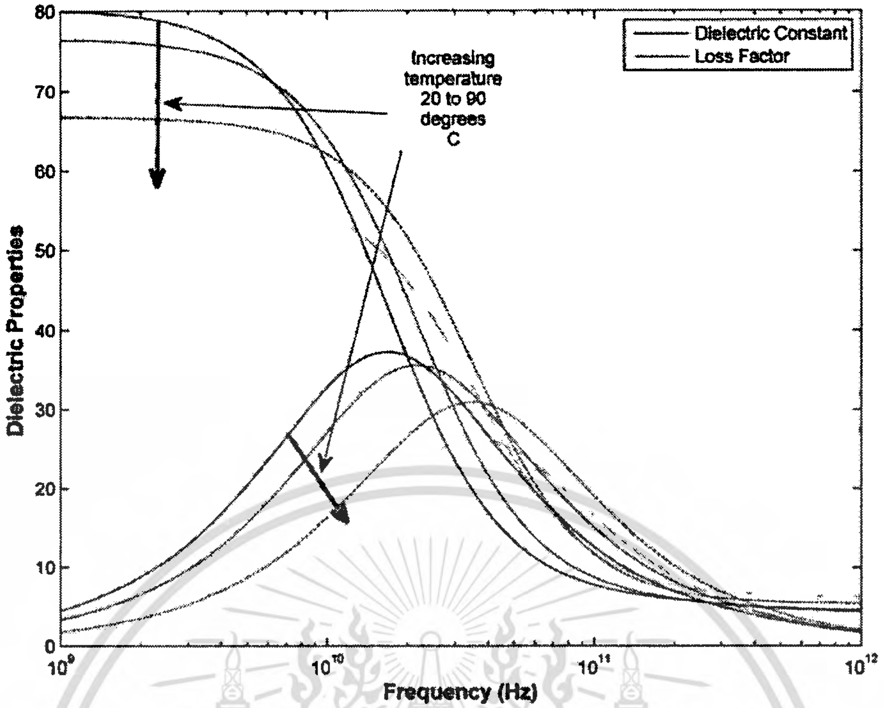


Fig. 2.4. The depiction of dielectric properties varying with temperature and frequency [25].

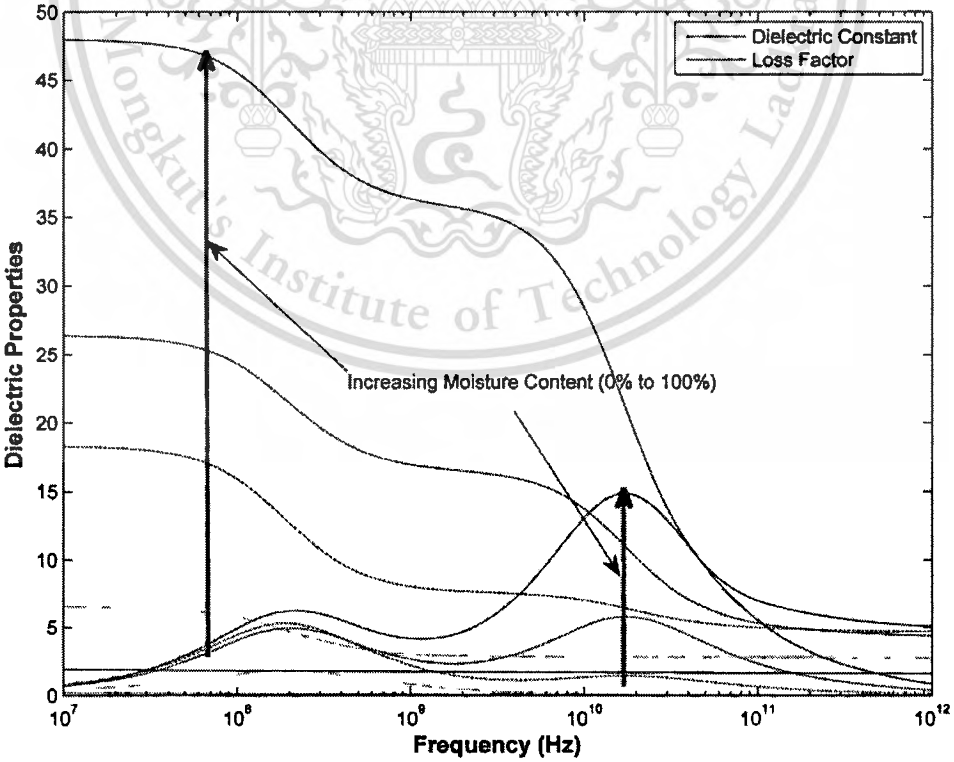


Fig. 2.5. The dielectric properties of wood [25].

Permeability, μ', describes the response of a material to a magnetic field, while μ'' represents the magnetic loss factor due to relaxation and resonance processes under the influence of an alternating magnetic field [24].

Permeability controls the penetration depth: the higher the permeability, the less an electromagnetic wave will penetrate into the material.

2.2.7 Penetration Depth

Penetration depth, d, is a measure of the depth of microwave penetration into a material. The penetration of the field is defined as the distance from the surface of the material at which the magnitude of the field strength reduces to $1/e$ (= 0.368) of its value at the surface [8]. The penetration depth of the electric field can be expressed by Equation (2.25).

$$d = 1/\alpha \tag{2.25}$$

where α is attenuation factor and can be presented as

$$\alpha = \omega \left(\frac{\mu_0\mu'\varepsilon_0\varepsilon'}{2}\right)^{1/2} \left[(1+(\varepsilon''/\varepsilon')^2)^{1/2} - 1\right]^{1/2} \text{ Np/m} \tag{2.26}$$

$$\alpha = 2\pi f \left(\frac{\mu_0\mu'\varepsilon_0\varepsilon'}{2}\right)^{1/2} \left[(1+(\tan\delta)^2)^{1/2} - 1\right]^{1/2} \tag{2.27}$$

As seen in Equation (2.27), the penetration depth is inversely proportional to the frequency of electromagnetic field.

The power penetration depth, D_p, can be defined as the distance at which the power density reduces to $1/e$ of its value at the surface[34] and is half of the value of the electric field penetration depth, d.

$$D_p = \frac{1}{2\alpha} = \frac{d}{2} \tag{2.28}$$

Or

$$D_p = \frac{1}{\frac{2\pi f}{v}\left[\frac{\varepsilon'\left(1+(\tan\delta)^2\right)^{1/2} - 1}{2}\right]^{1/2}} \tag{2.29}$$

for small $\tan\delta$, in Equation (2.29) reduces to

$$D_p = \frac{c\sqrt{\varepsilon'}}{2\pi f\,\varepsilon''} \tag{2.30}$$

2.2.8 The dielectric heating equation

The dielectric heating equation in microwave heating can be expressed as

$$\mathrm{p} = 2\pi f \varepsilon_0 \varepsilon'' E_{rms}^2 \tag{2.31}$$

2.2.9 Thermal runaway

Thermal runaway, as shown in Figure 2.6, is a condition which arises when the power dissipation in a small elemental volume within a workload exceeds the rate of heat transmission to its surroundings such that the rate of increase in enthalpy is greater than in its neighbors [23]. The temperature increases faster than in the surroundings until decomposition occurs. Thermal runaway invariably degenerates into arcing, and it is often difficult to decide which sequence of events has occurred.

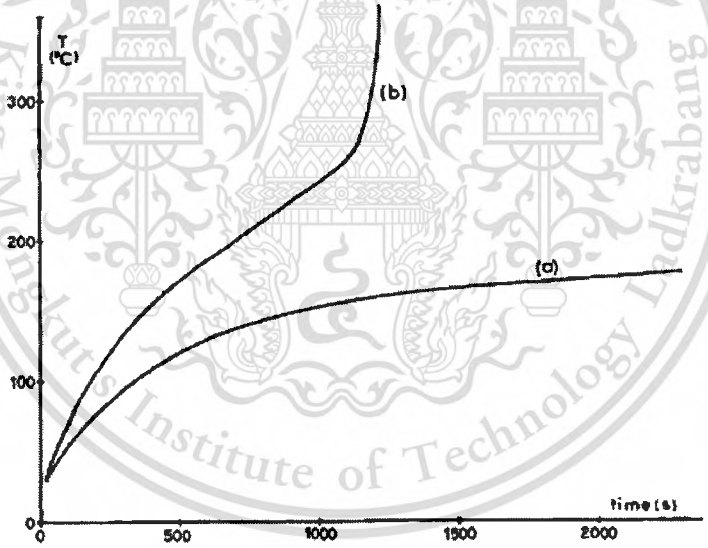


Fig. 2.6. Normal response (a) and thermal runaway (b) under microwave heating [23].

In real experiments, the mechanisms involved in thermal runaway are very complicated and almost impossible to quantify. It is a statistical phenomenon around which operational conditions are set so that the probability of a runaway incident is within acceptable bounds, conditions which can only be determined by experiment.

The guidelines for design to avoid thermal runaway:

(a) Operate with as low a mean power density as possible;

(b) Design the feed system of the cavity (applicator) to give as uniform an illumination as possible, specifically avoiding field concentrations;

(c) Ensure that the workload is uniformly spread in the cavity

2.2.10 Cavity and feeding systems

The cavity is a space enclosed by inner metal walls in which workload interacts with microwave. There are many ways to couple microwave energy into the cavity. A waveguide is generally used to launch the energy from the microwave source into the cavity as it has the advantage of minimizing the reflected power. Its position is important to determine the distribution of energy inside the cavity [23,24].

From review of the theories as previously mentioned, this dissertation focuses on the design and fabrication of the multi-feed cavity which allows for uniform heating to mitigate the thermal runaway effect of the workload in the carbonization reactor. The design and fabrication will be described in chapters 3 and 4.

2.3 Chaotic system

Chaos refers to one type of the complex dynamical behaviors that possesses some of the very special features such as extreme sensitivity to tiny variations of initial conditions, long-term unpredictation, bounded and unbounded trajectories in the space, bifurcation, fractions and strange attractors [26-28]. Examples of chaotic systems include nobody problem, turbulent flow of fluids, liquid mixing, chemical reactions, biological and economic systems, and robotic systems [29,33]. The logistic map is a popular model for the growth of a single-species population having non-overlapping generations. The simple modified mathematical form of the logistic map is given as Equation (2.32), where a is the chaos parameter between 3.5 to 4. As shown in Figure. 2.7, chaos is sensitive to the initial condition. Mathematically, the logistic map equation is written as

$$f(x) = rx(1-x) \tag{2.32}$$

where:

x is a number between zero and one,

r is a positive number and represents the chaotic growing.

2.3.1 Bifurcation

Bifurcation is a two-dimensional diagram to observe the solution value of variation behavior of a system when a coefficient of the system is changed. As seen in Figure. 2.7, when a coefficient of the logistic equation, r, is varied from 3.4 to 4.

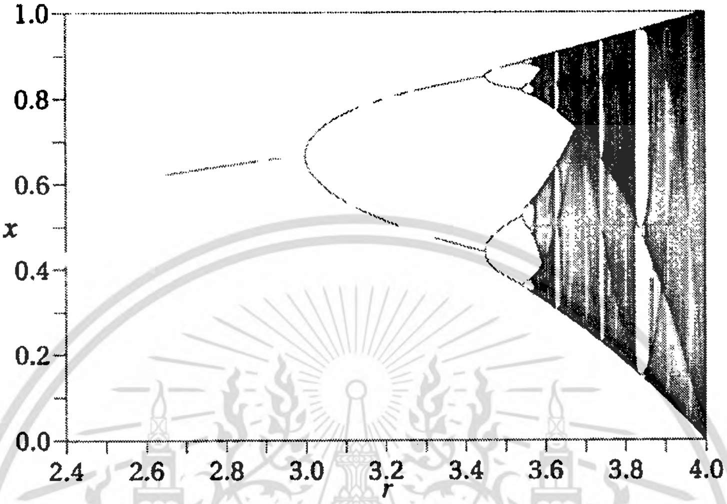


Fig. 2.7. Bifurcation diagram of logistic map [29].

Chapter 3

Design of the continuous microwave biomass carbonization system

Chapter 2 reviews the principle and theories used in this thesis while this chapter presents the design of the continuous microwave biomass carbonization system. The requirements of this continuous microwave biomass carbonization system are tabulated in Table 3.1.

Table 3.1 Technical data of the continuous microwave biomass carbonization system.

Item	Description	
1	Quantity of charcoal yields	50 kg/hr
2	Quantity of wood vinegar	15 lit/hr
3	Electricity generated	10 kW, 220V, 50 Hz
4	Operating system type	Continuous

As the product yields by carbonization of the traditional biomass (i.e., palm shells) was 120 kg/25 hours as shown in Table 3.2, this research work thus assumed that approximately 350 kg/hour of coconut shells, raw material of this work, was required as input of this carbonization system to obtain the product yields as seen in Table 3.1.

Table 3.2 Product yields by carbonization of the traditional biomass (palm shell).

Item	Product	%wt	Yields
1	Charcoal	20 – 25	30 kg.
2	Wood vinegar	17 – 25	25 lit.
3	Gas	~ 50	~ 60 m^3

3.1 Review of continuous microwave biomass carbonization system

Crushed biomass waste is conveyed with the bucket elevator to a hoper on top to dehydrate and the carbonization reactor inside the cylindrical cavity fixed with

10 microwave sources is employed to carbonize the crushed biomass. The charcoal yield is conveyed out from the continuous microwave biomass carbonization system by a screw-conveyer while the gas yield is transported by a pipe on top of the reactor to a condensation unit to be condensed into wood vinegar. Meanwhile, uncondensed gases are transferred to a gas purifying unit and treated to be suitable for use in electricity generation.

Figure. 3.1 illustrates the conversion pathway of the continuous microwave biomass carbonization system. The process begins with biomass waste as input and ends with three forms of product yields: charcoal, wood vinegar (bio-oils), and fuel gas. Figure. 3.2 shows the schematic of a full-scale microwave carbonization system.

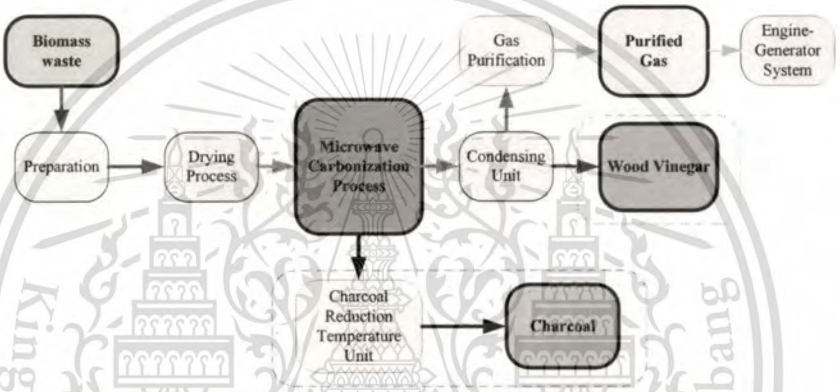


Fig. 3.1. Biomass carbonization conversion pathway.

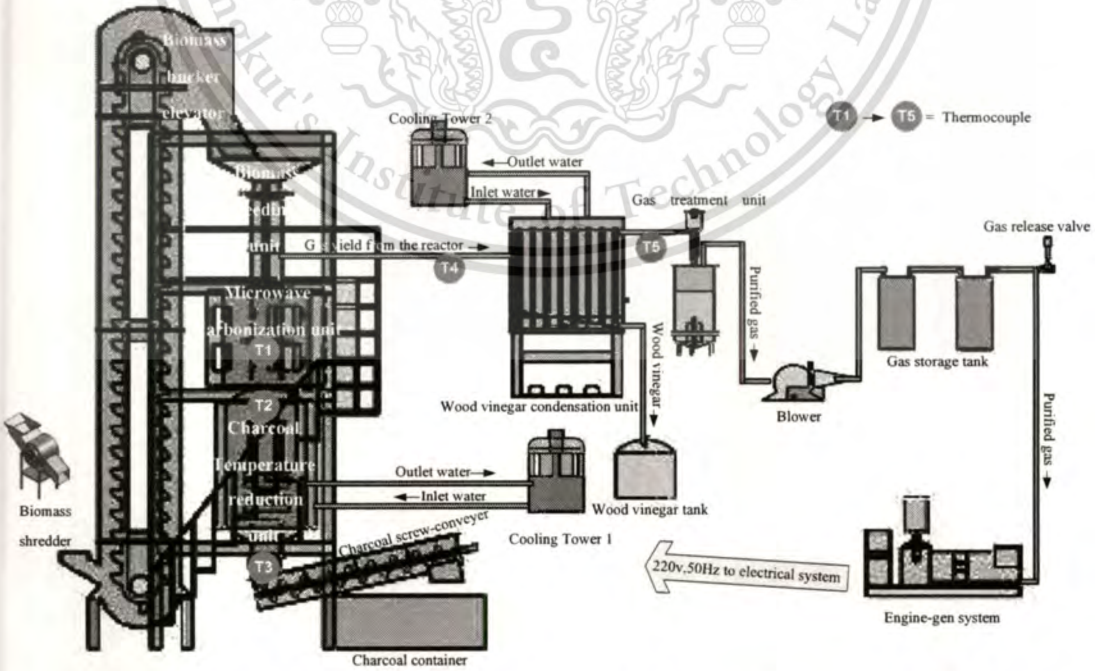


Fig. 3.2. Full-scale continuous microwave biomass carbonization system.

On the aspect of the design of the carbonization system of this thesis, the focus is specifically on the carbonization heating system design, which consists of the design of carbonization reactor and multi-feed microwave cavity.

3.2 Carbonization reactor (Low cement castable reactor) design

Table 3.3 Dielectric properties and penetration depth of the alumina ceramic mixed with silica (25°C) at 2.45 GHz.

Material	Dielectric Properties		Penetration Depth	
	ε	ε	*d* (cm)	*Dp* (cm)
Alumina ceramic mixed with silica(25°C) at 2.45 GHz	8.9	0.009	12.65	6.32

Table 3.3 presents the dielectric properties and the penetration depth of alumina ceramic mixed with silica (25°C) at 2.45 GHz. It was found that the mixture is a suitable material for a carbonization reactor and that the thickness of reactor walls should be less than 6.32 cm as microwave energy can still go through the walls of this thickness or less to react with biomass inside. To meet the requirements in Table 3.1, this research calls for a cylindrical low cement castable reactor with organic fiber of alkaline resistance and maximum service temperature of 1400 °C. The reactor is of 0.296 m in internal diameter, 0.05 m in thickness, 0.9 m in height, and 0.85 m^3 in volume of reaction. Figure 3.3 depicts the dimensions of the carbonization reactor.

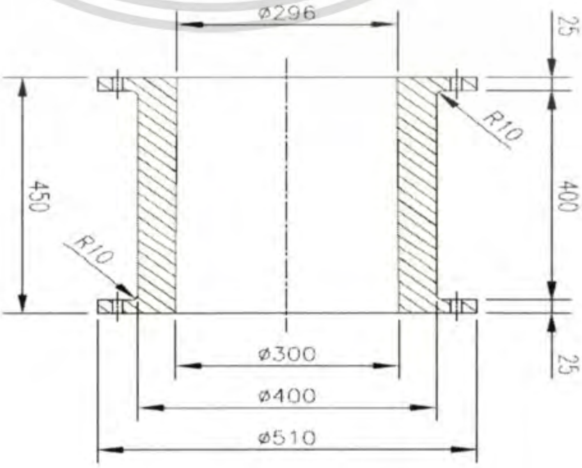


Fig. 3.3. The dimensions of the carbonization reactor (top and bottom).

3.3 Design of multi-feed microwave cavity

Typical carbonization temperatures for most biomass are 200-600 °C. Also, design of a multi-feed microwave cavity must allow for optimal control of the heating rate to improve heating uniformity [23,25,34,35]. Therefore, multi-mode microwave radiation was employed in this research work to heat the multi-feed microwave cavity as shown in Figure. 3.4. Ten rectangular openings are drilled around the cavity, with each opening fixed with a microwave source, each of which consists of a magnetron and a waveguide. The microwave sources are installed in two parallel levels of five sources for each level. In the center of the cavity vertically lies a cement castable reactor, through which biomass to be reacted is passed. The reactor is made from cement to allow penetration by microwave radiation.

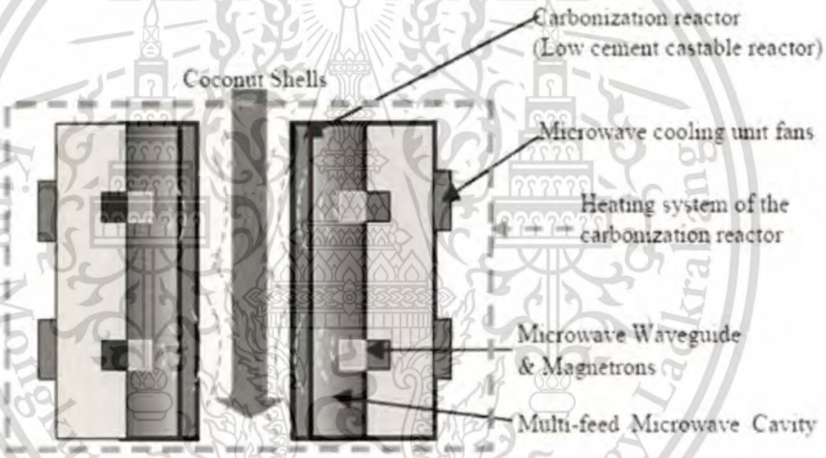


Fig. 3.4. The depiction of multi-feed microwave cavity.

A heating system using microwave without stirring mechanism in which the heat can evenly distribute throughout biomass or load is designed. The absence of stirrer reduces the complexity of the design and construction of the system. As a matter of fact, the microwave reactor makes impossible installation of a stirrer because the latter would bounce off the electromagnetic waves, thereby causing uneven distribution of heat inside the reactor.

3.3.1 Waveguide and cavity for heating inside the carbonization reactor

An air-filled WR340 waveguide with dimensions of a = 86 mm, b = 43 mm and 211.5 mm. in length, operating at 2.45 GHz with dominant TE_{10} mode are applied in this research. The modes inside the cylindrical cavity are changed to multi-mode when the electromagnetic wave TE_{10} mode is guided by waveguide into the cylindrical cavity. The pattern of the wave that travels in the waveguide is identical in all microwave sources M1-M5 and M1'-M5'.

The calculation of mode propagation inside the carbonization reactor is very complex since the raw materials inside the carbonization reactor are of varying dimensions and sizes.

3.4 Design of uniform heating in the carbonization reactor

After the design of the carbonization reactor was complete, the next challenge is how to ensure uniform heating inside the carbonization reactor. This dissertation has applied chaotic signals to regulate the pattern of microwave radiation to ensure uniform heating inside the reactor, and has termed it the chaotic control system. Moreover, the chaotic control system can produce several uniform mode patterns. A diagram of a chaotic signal pattern system is presented in Figure 3.5.

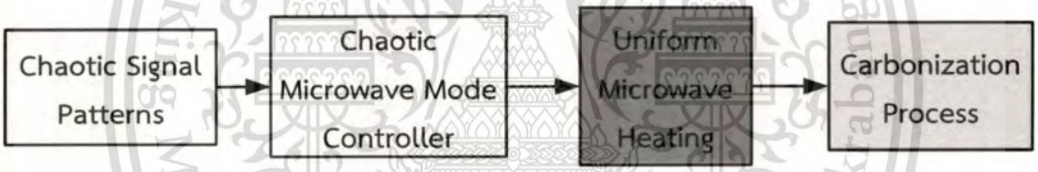
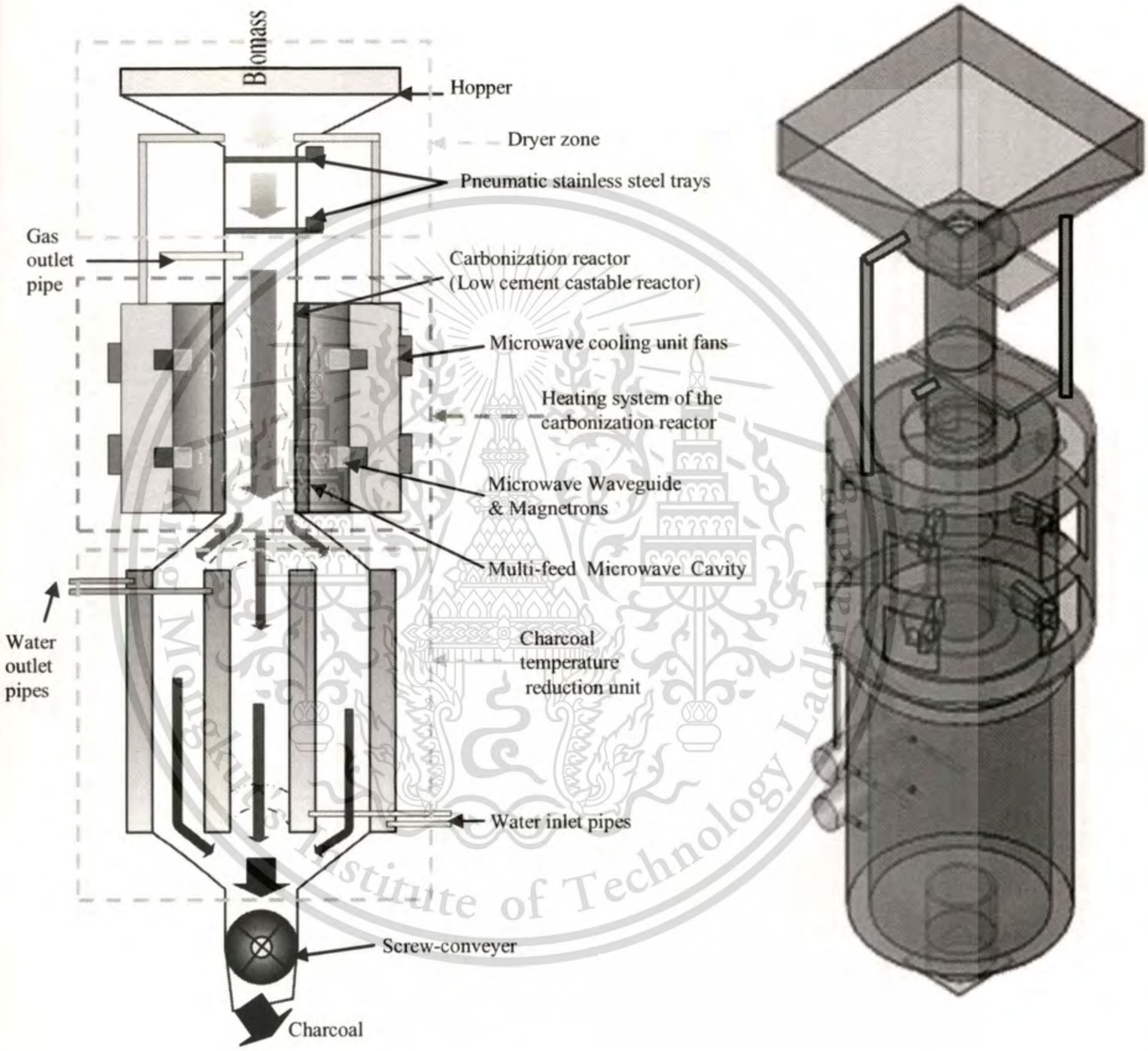


Fig. 3.5. Diagram of a chaotic signal pattern system.



a. b.

Fig. 3.6. Frontal cross-section view of partial carbonization process (3.a); Isometric view of partial carbonization process (3.b).

Chapter 4

Fabrication of continuous microwave biomass carbonization system

The snapshot of the continuous microwave biomass carbonization system in this dissertation is presented underneath, the entire system of which is 7 meters in height and covers an area of 25 square meters.

Fig. 4.1. A snapshot of the continuous microwave biomass carbonization system.

4.1 Biomass feeding system

In the feeding system, crusted biomass waste is conveyed by a bucket elevator to the hoper on top to dehydrate. After dehydration, the dried biomass waste is fed down into the carbonization reactor through the cylindrical steel pipe of 0.30 m in inner diameter. The amounts of dried biomass fed into the reactor are regulated by two pneumatic stainless steel trays which help prevent gas leakage from the reactor.

4.2 Carbonization reactor (Low cement castable reactor)

The carbonization reactor in this dissertation is made up of a cylindrical low cement castable with organic fiber resistant to alkaline and maximum service temperature of 1400 °C. The reactor has 0.30 m in internal diameter, 0.07 m in thickness, 0.9 m in height, and 0.85 m^3 in volume of reaction. The top part of the reactor is connected to a biomass feeding pipe while the bottom part to a charcoal temperature reduction unit with all the joints sealed by ceramic fiber to prevent a leakage of gases. A hole is bored in the top part of the reactor and a 2-inch steel pipe is fitted to the hole as a passage of carbonization gas yields, the flow rate of which is controlled by a blower.

4.3 Heating system of carbonization reactor

The heating system of the carbonization reactor as shown in Figure.3.4. consists of: (1) the innermost low cement castable reactor, (2) the microwave sources in the middle, and (3) the outermost layer with cooling fans. The low cement castable reactor is the central cylindrical passage, through which the biomass passes and reacts with microwave. The middle layer is a multi-feed microwave cavity comprising two rows of five magnetrons on each row (totaling 10). The magnetrons to heat the biomass are of OM75S-020 model of Samsung with 2.45 MHz frequency and 0.85 kW (4 kV, 300mA) each for a combined maximum of 8.5 kW. The outermost layer is installed with 10 cooling fans to transport the heat loss from the rear of the microwave sources to the hopper to pre-heat the biomass prior to passing down through the low cement castable reactor. The shutters on the top and bottom of the castable reactor prevent the leakage of microwave radiation. Figure. 4.2 is the snapshot of the actual heating system of the carbonization reactor. Each microwave source of the multi-feed microwave cavity is controlled for uniform heat distribution by 10 solid state 10A/220V relays which are in turn controlled by the Programmable Logic Controller (PLC).

Fig. 4.2. A snapshot of the heating system of the carbonization reactor.

4.4 Charcoal temperature reduction unit

The unit consists of two stainless steel cylindrical hollow tubes of different sizes with the smaller tube placed inside in the center of the larger one. Cool water from cooling tower 1, entering from the inlets at the bottom and discharged through the outlets at the top, is circulated inside the hollow parts between both tubes. The solid yield from the reactor is then passed through to reduce the temperature. On the top part of the charcoal temperature reduction unit is a thermocouple type K (T2), as shown in Figure. 3.2, to measure the temperature of the solid yield from the reactor. Meanwhile, at the bottom part of the unit is the same type of thermocouple (T3), as seen in Figure. 1, to measure the solid yield temperature after passing through the charcoal temperature reduction unit. Afterward, the obtained solid yield (i.e., charcoal) is transported by the screw conveyer to the storage container as shown in Figure. 3.2.

4.5 Condensing unit

As shown in Figure. 3.2, the condensing unit in this study is of the vertical shell and tube condenser type with cooling water as heat exchanger. The unit consists of 120 tubes, each with 0.038 m in diameter and 1.15 m in height. Cool water from cooling tower 2, entering from the upper inlets and released through the lower outlets, is circulated inside the hollow parts of all 25 tubes of the condensing unit. The gas yields from the reactor, passing through the condensing unit, are condensed into wood vinegar.

4.6 Gas treatment unit

The uncondensed gases leaving the condensing unit are treated with water spray and then rock bed filter inside the gas treatment unit to remove moisture and tar. The two-stage filtering is required to ensure that the fuel gases are sufficiently clean for use in the engine-generator system of this paper.

4.7 Engine – Generator system

The engine-generator system, which produces 10 kW, 220 V, 50 Hz of electricity to operate the entire carbonization process, is fueled with gasoline in the first run of the process and then with the remaining fuel gas from previous carbonization in the subsequent runs. The system is able to generate sufficient electricity to satisfy the power requirement of the carbonization process.

4.8 Control unit

All operating system is automatically controlled by a PLC. The process temperature can be monitored with a temperature controller in the control panel and seven K-type thermocouples are used. Temperature readings in the reactor and at various points in the system are assigned as T1-T5 in Figure 1, where T1 – T3 denote the temperatures inside the reactor, T4 of the condensation system, and T5 of the gas system. The functioning and status of the system are viewable on a touch screen display.

Fig. 4.3. A snapshot of partial carbonization process (back view).

Chapter 5

Experiment and Results

5.1 Experiment and Results

Coconut shells crushed into small chips of 2-4 cm. in size as shown in Figure.5.1 were used in the experiment as raw material, and 350 kg/hr at 50 % mc of the crushed coconut shells were fed into the proposed system. The carbonization process started with filling the reactor with the dried coconut shells which were then heated up by all ten microwave radiation sources until the reactor temperature (T1) reached 400, 450 and 500 °C depending on the requirement. This period is called the startup period. After the temperature reached the defined temperature began the operating period, during which the charcoal yields of the microwaved and then cooled down coconut shells were transported by the screw conveyer to storage containers. The temperature was maintained by automatic on/off cycle of each microwave source at a defined temperature until the end of the operating period. The cycle was controlled by the PLC which switched on (off) the microwave sources if the temperature dropped below (reached) the defined temperature. Thermocouples (T) were installed in various locations to measure the operating temperatures: T1 in the center of the reactor, T2 at the bottom of the reactor, T3 on top of the cooling zone, T4 at the bottom of the cooling zone, and T5 in the purifying gas pipe.

Fig. 5.1. Coconut shell chips of 2-4 cm in size used as raw material.

Table 5.1 shows the optimal configuration of process parameters with the duration of continuous operation of 10 hours. Notwithstanding, it should be noted that the entire process required approximately 13 hours: two hours for the startup, 10 for the actual operation, and one for the end period.

Table 5.1 The optimal configuration of process parameters at the reference temperatures of 400, 450, 500 °C.

Item	Rate	
	Startup period	Operation period
-Screw conveyer speed (rpm)	0	9
-Blower speed (rpm)	25	25
-Water flow rate at cooling tower1 (cc/s)	5	280
-Water flow rate at cooling tower2 (cc/s)	50	220
-Pneumatic stainless steel trays (time/Hr)	0	12

Figure 5.2 is the diagram of the uniform heating control system whereby the chaotic pattern signals are input of microwave sources and these pattern signals are in turn controlled by the PLC.

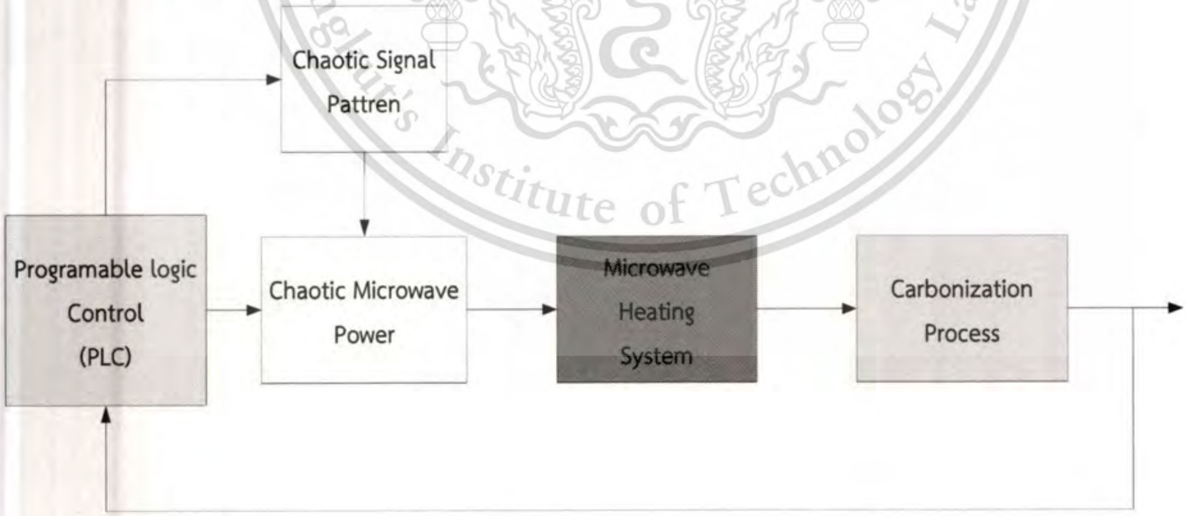


Fig. 5.2. Diagram of the uniform heating control.

To prove that the chaotic pattern signals do heat more efficiently, the cycle and the random input patterns, as shown in Figures. 5.3 – 5.7, are compared in the results. The cycle of signals levels are changed every 5 minutes.

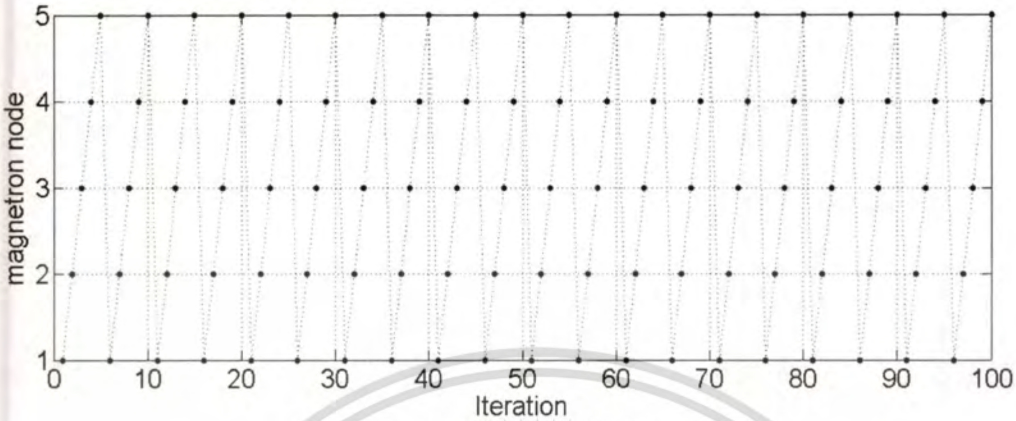


Fig. 5.3. The cycle pattern.

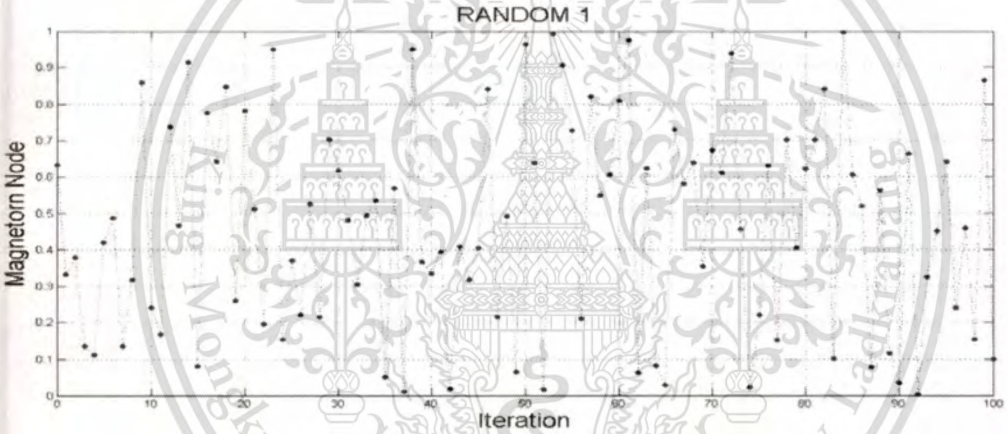


Fig. 5.4. The random pattern.

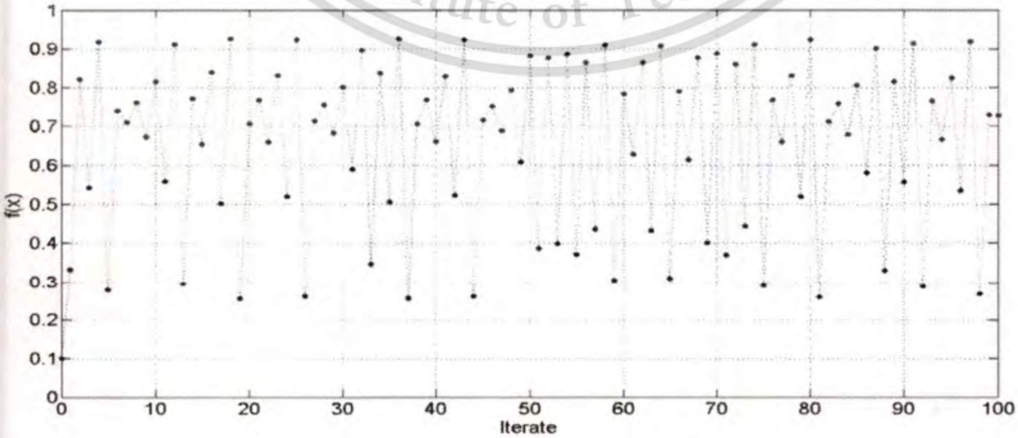


Fig. 5.5. The chaotic pattern (Logistic X= 3.7).

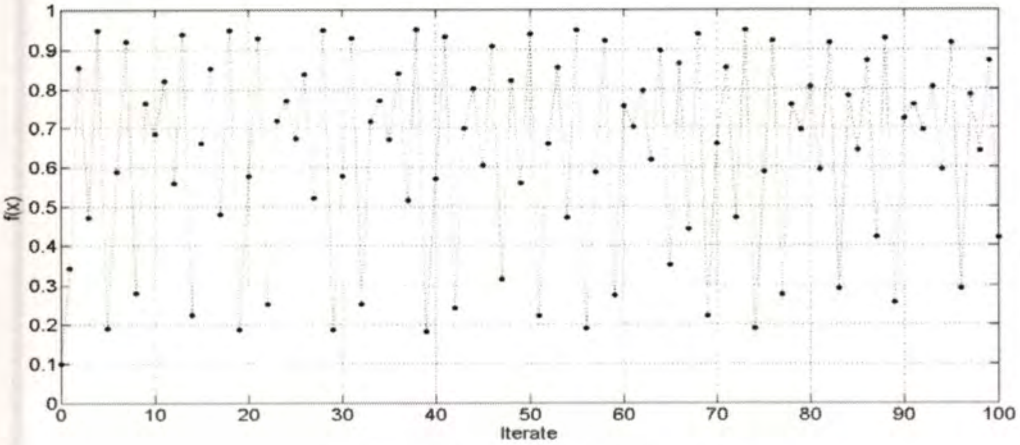


Fig. 5.6. The chaotic pattern (Logistic X= 3.8).

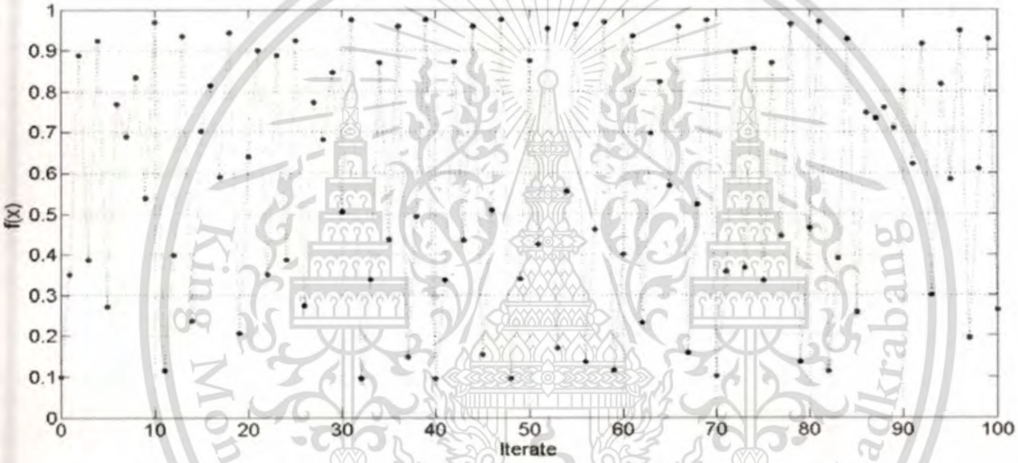


Fig. 5.7. The chaotic pattern (Logistic X= 3.9).

Table 5.2 The microwave sources by the range of f(x) values.

f(x)	≤ 0.2	0.2>,≤ 0.4	0.2>,≤ 0.4	0.2>,≤ 0.4	0.2>,≤ 0.4
Microwave source	M1 , M1'	M2 , M2'	M3 , M3'	M4 , M4'	M5 , M5'

Table 5.2 shows the operating status of each microwave source by the range of f(x) values. The temperature versus time characteristics during the startup period testing when the coconut shells were heated up by all signal patterns at 450°C are presented in Figure. 5.8, while the operating time versus temperature characteristics are presented in Figure. 5.9. The electric power consumptions at startup period and operating period of signal patterns comparision are presented in Figure. 5.10 and Figure. 5.11, reapectively. Table. 5. Shows the comparison of average electric consumption of each signal patterns form the startup to the end period.

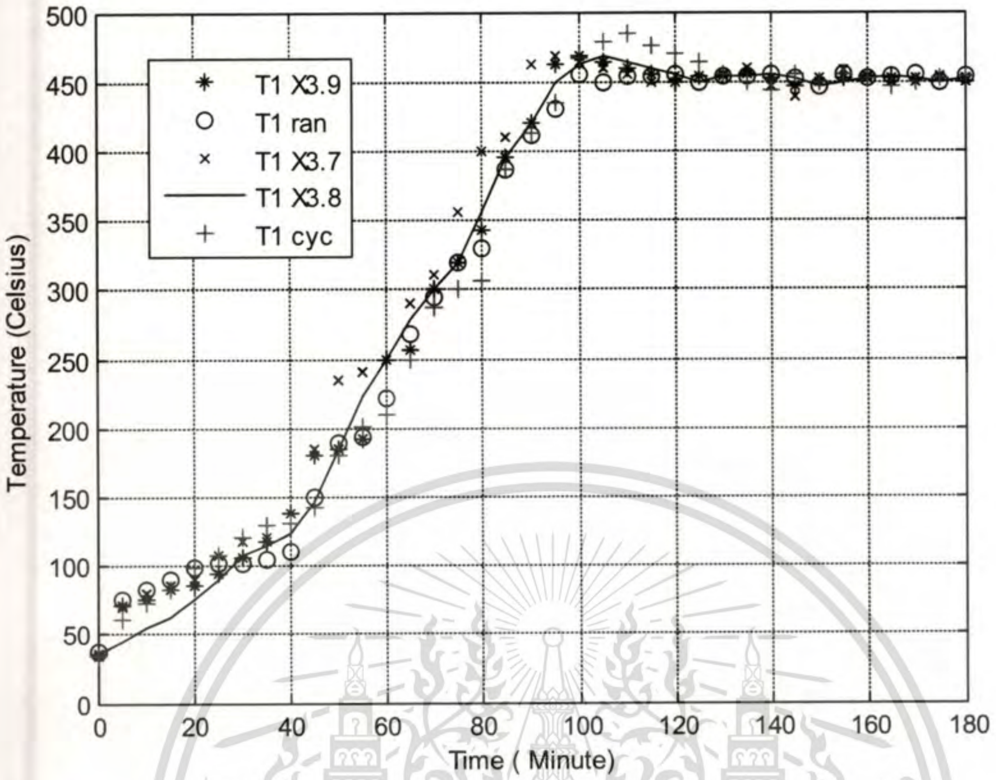


Fig. 5.8. The temperature vs time characteristics at startup period of signal patterns.

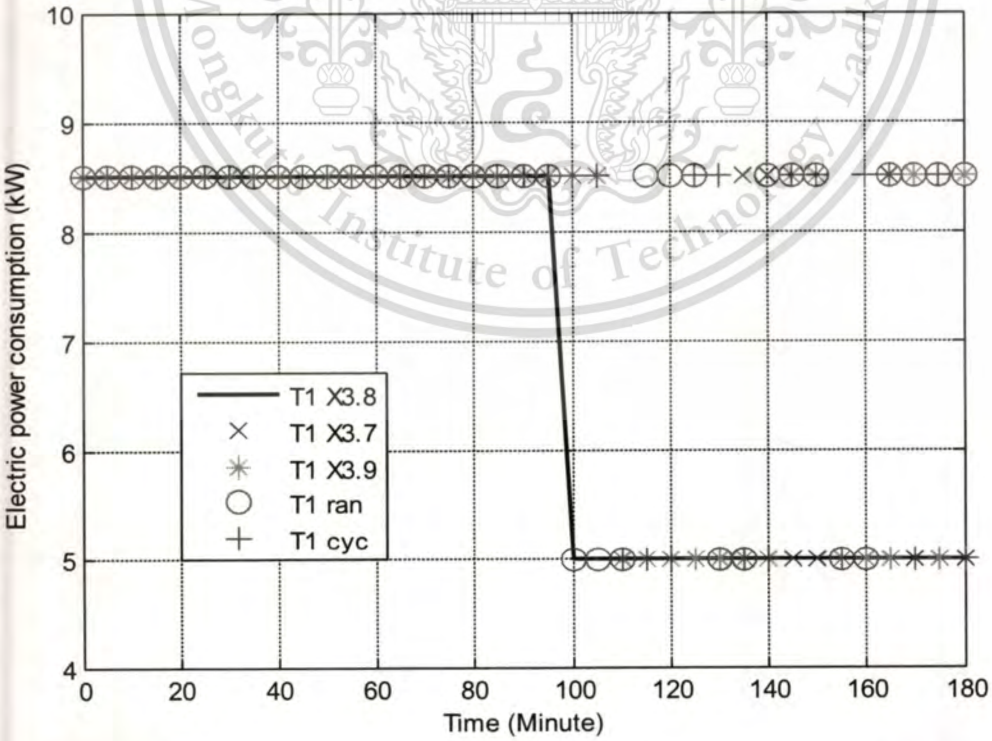


Fig. 5.9. The electric power consumption vs time characteristics at startup period of signal patterns.

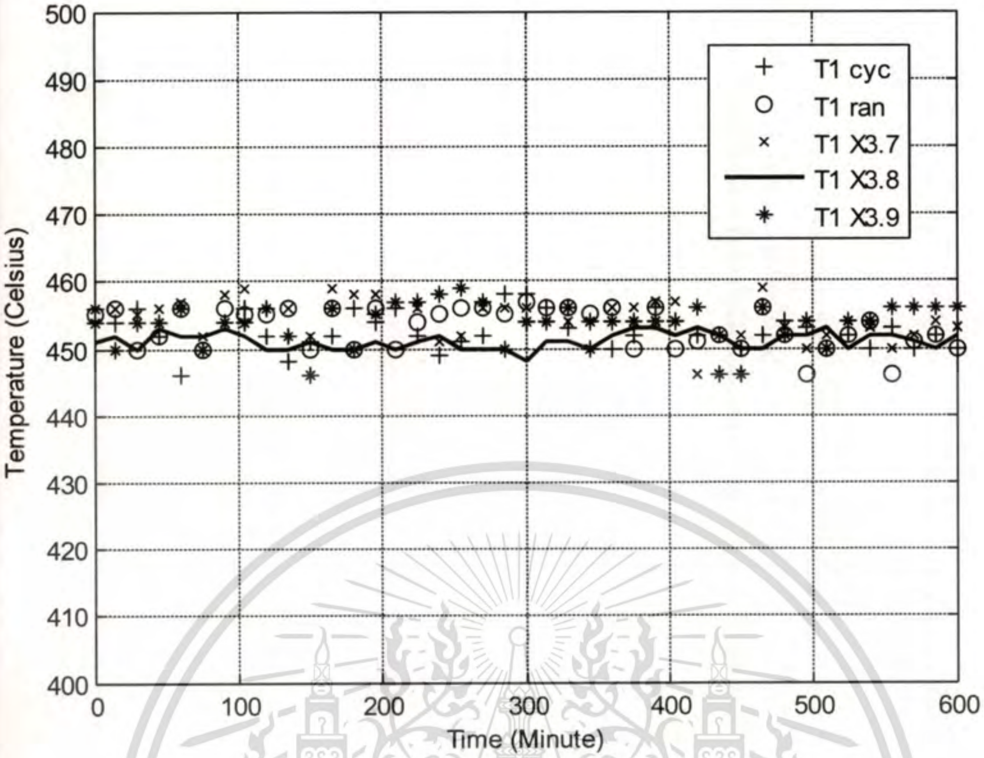


Fig. 5.10. The temperature vs time characteristics during operating time of signal patterns.

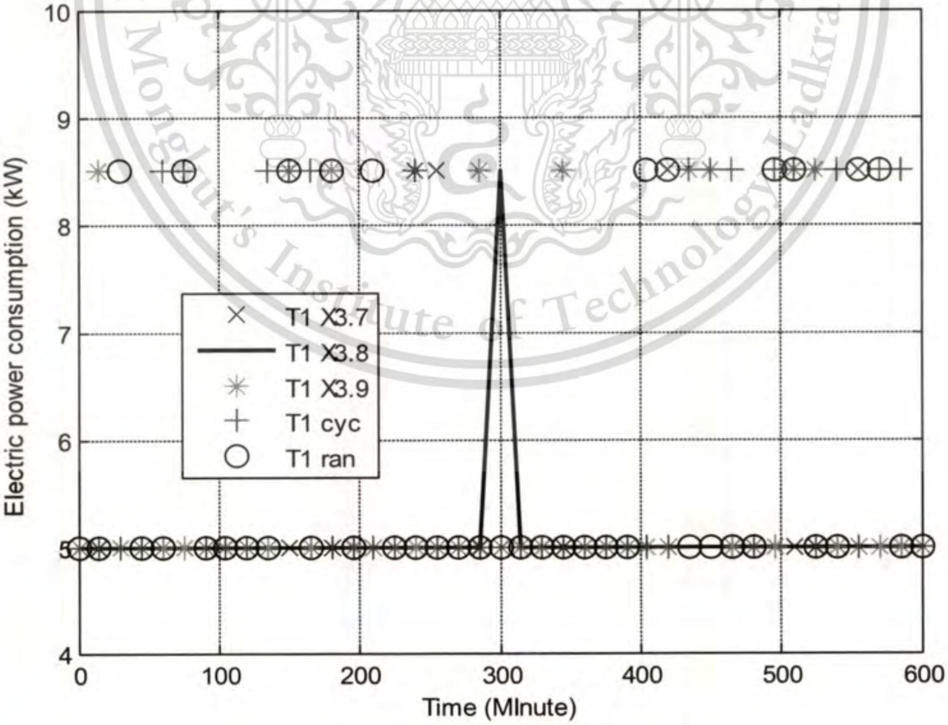


Fig. 5.11. The electric power consumption vs time characteristics during operating time of signal patterns.

Table 5.3 The comparison of average electric consumption of each signal patterns form the startup to the end period.

Signal pattern	X = 3.7	X = 3.8	X = 3.9	Cycle	Random
Average power (kW/h)	6.39	5.94	6.57	6.93	6.84

As observed in Figures. 5.8-5.11 and Table 5.3, highly stable heating temperature characteristic was generated by the chaotic pattern (Logistic X= 3.8). Thus, this pattern can be utilized to generate uniform heating inside the carbonization reactor.

The experiments in this work applied the chaotic pattern (Logistic X= 3.8) as input pattern of microwave sources to carbonize the coconut shells at 400, 450 and 500 °C. The experiment results at the startup and during the operating time for all three heating temperatures (i.e., 400, 450 and 500 °C) are presented in Figures. 5.12-5.15.

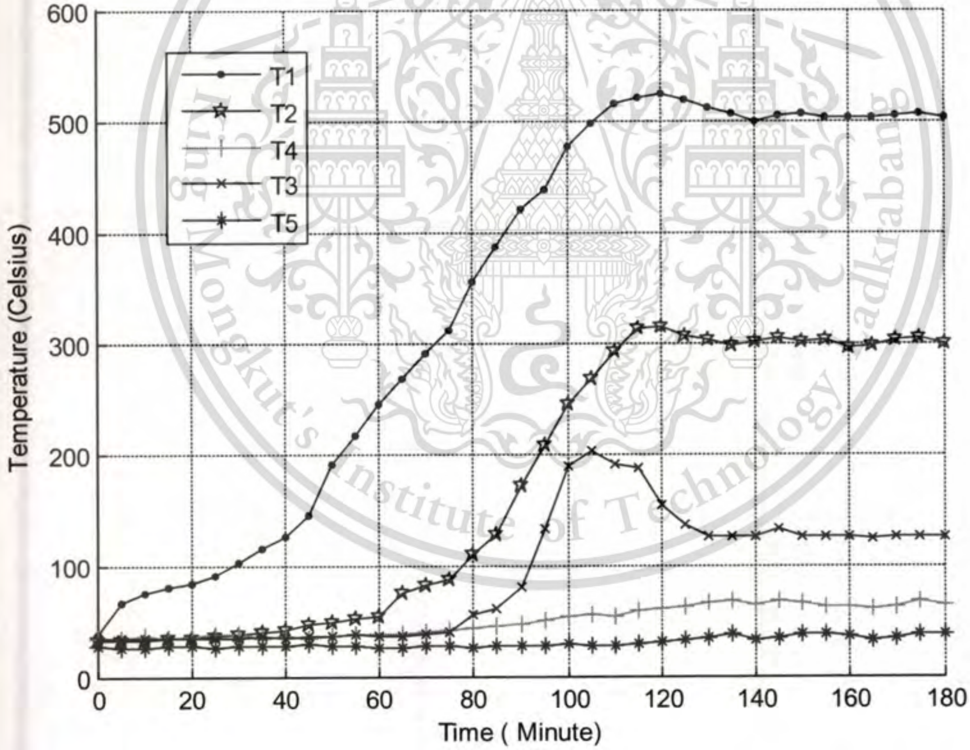


Fig. 5.12. The temperature vs time characteristics at startup period (temperature *T vs.* heating time *t*, (recorded every 5 min)) at 500 °C.

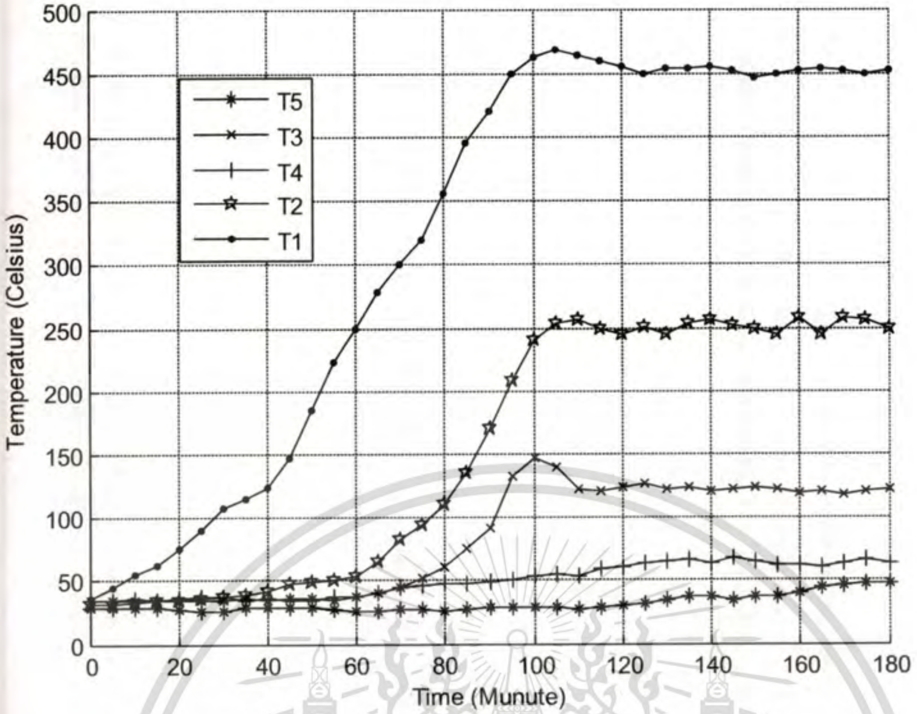


Fig. 5.13. The temperature vs time characteristics at startup period (temperature *T vs.* heating time *t*, (recorded every 5 min)) at 450 °C.

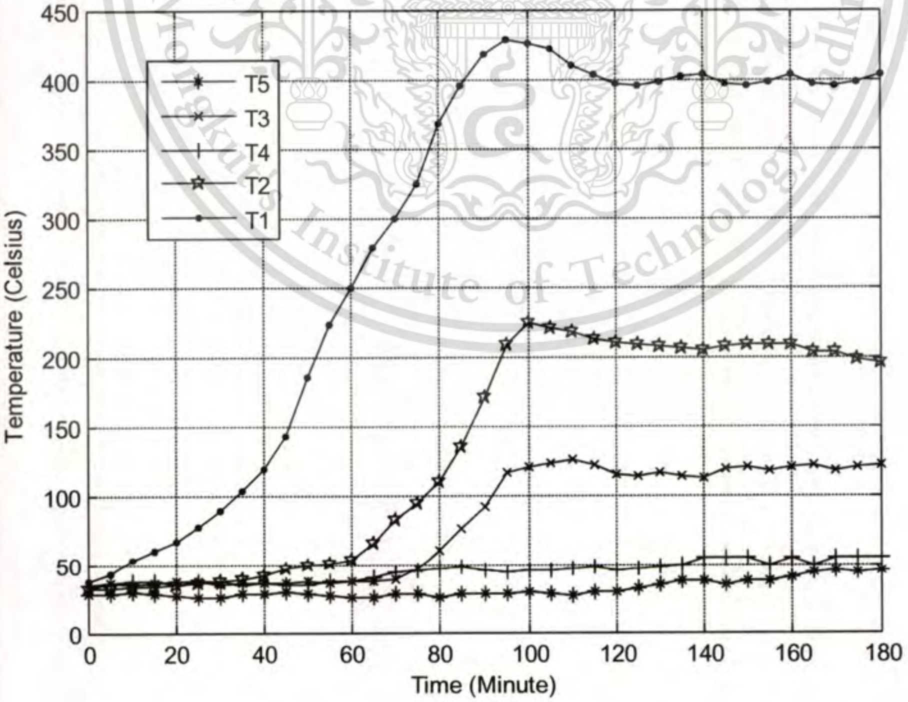


Fig. 5.14. The temperature vs time characteristics at startup period (temperature *T vs.* heating time *t*, (recorded every 5 min)) at 400 °C.

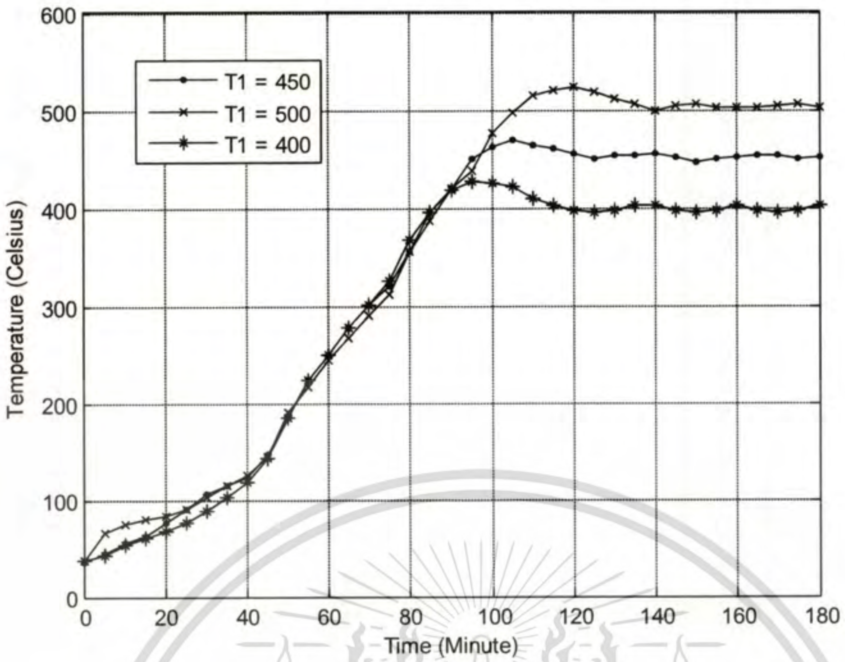


Fig. 5.15. The comparison of the temperature vs time characteristics at startup period (400, 450 and 500 °C).

The analysis results with Oxygen Bomb Calorimeter Kika® Labortechnik C5000 of the charcoal product yields in comparison with the raw material (i.e., coconut shells) are presented in Table 5.4. The heating values of the charcoal yields are presented in Table 5.5. The chemical components and pH values found in wood vinegar tested by Gas Chromatography-Mass Spectrometry are respectively presented in Tables 5.6 and 5.7.

Table 5.4 Analysis results of coconut shell (raw material) vs charcoal product yields.

	Coconut shell	Product yield		
		400°C	450°C	500°C
Total moisture (wt.%)	10.53	3.74	3.35	3.18
Volatile mater (wt.%)	78.3	10.92	11. 61	14.32
Fixed carbon content (wt.%)	20.96	80.02	80.4	81.2
Ash (wt.%)	0.74	5.32	4.54	4.48

Table 5.5 The calorific values of charcoal product yields heated at different temp.

Temperature	Calorific value (kcal/kg)
400 °C	7,260
450 °C	7,180
500 °C	7,340

Table 5.6 Percent of the chemical components found in wood vinegar of coconut shell samples heated at 400, 450, 500 °C.

No.	RT/min	ID	Area%		
			400 °C	450 °C	500 °C
1	4.21	toluene	n	n	12.29
2	4.23	propanoic acid	n	1.40	n
3	5.89	Furfural	4.82	4.80	3.98
4	6.34	2-furanmethanol	0.73	2.59	3.25
5	7.34	2-cyclopenten-1-one	n	0.52	n
6	7.41	ethanone	0.73	1.13	1.26
7	8.46	phenol	50.48	48.97	43.31
8	9.21	2-cyclopenten-1-one	2.22	2.00	2.57
9	9.68	phenol, 2-methyl	2.28	2.15	1.95
10	9.08	phenol, 4-methyl	2.71	2.76	2.95
11	10.37	phenol, 2-methoxy	8.99	8.4	8.25
12	13.05	2-methoxy-4-methylphenol	2.75	2.72	2.08
13	14.92	phenol, 4-ethyl-2-methoxy	1.70	1.21	0.88
13	15.97	phenol, 2, 6-dimethoxy	5.77	7.62	6.58
14	17.02	acetic acid	0.85	1.39	0.97
15	17.78	2-butanone	n	0.57	0.60

Table 5.7 pH of the wood vinegar from coconut shell samples heated at 400, 450, 500 °C.

Wood Vinegar : Distilled water	pH Values					
	100:0	1:100	1:200	1:300	1:400	1:500
400 °C	4.1	4.55	4.58	4.6	4.62	4.62
450 °C	3.75	4.15	4.19	4.22	4.23	4.23
500 °C	4.12	4.56	4.57	4.63	4.64	4.66

The effects of temperature on the product yields from the proposed carbonization system are illustrated in Figure. 5.16, while Figures. 5.17-5.19 shows a comparison of the product yields from this system with those of other research works [36],[37].

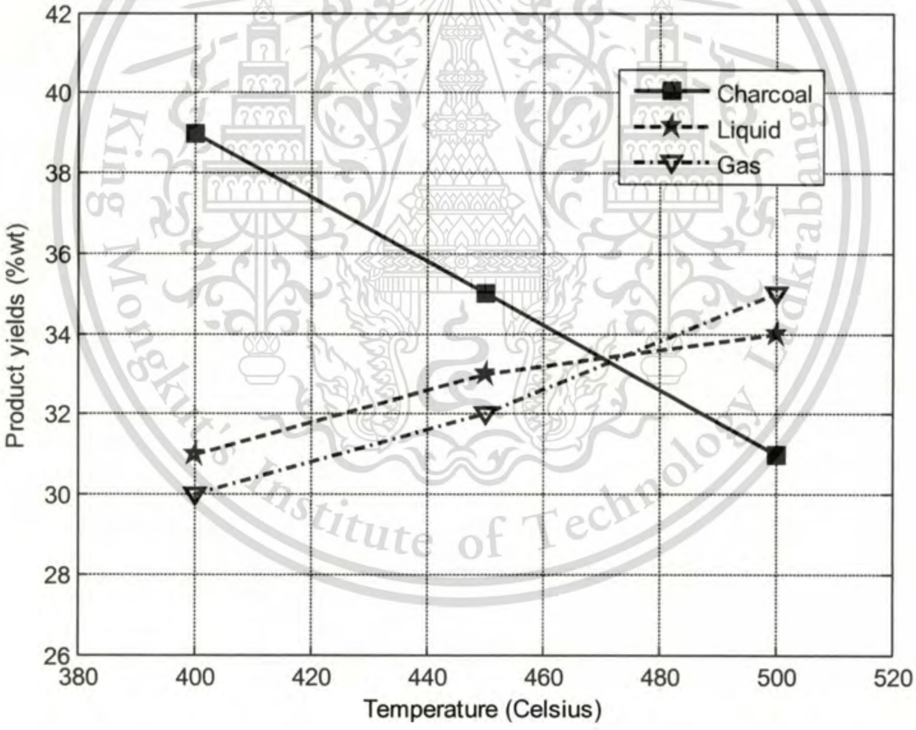


Fig. 5.16. The effects of temperature on product yields.

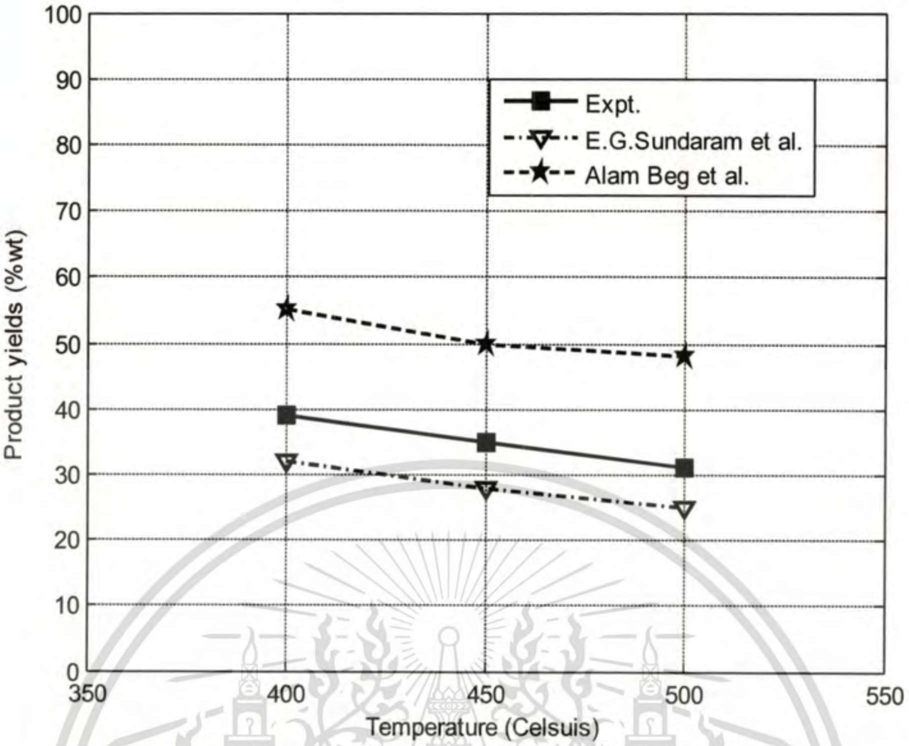


Fig. 5.17. The comparison of charcoal product yields of this system with other research works.

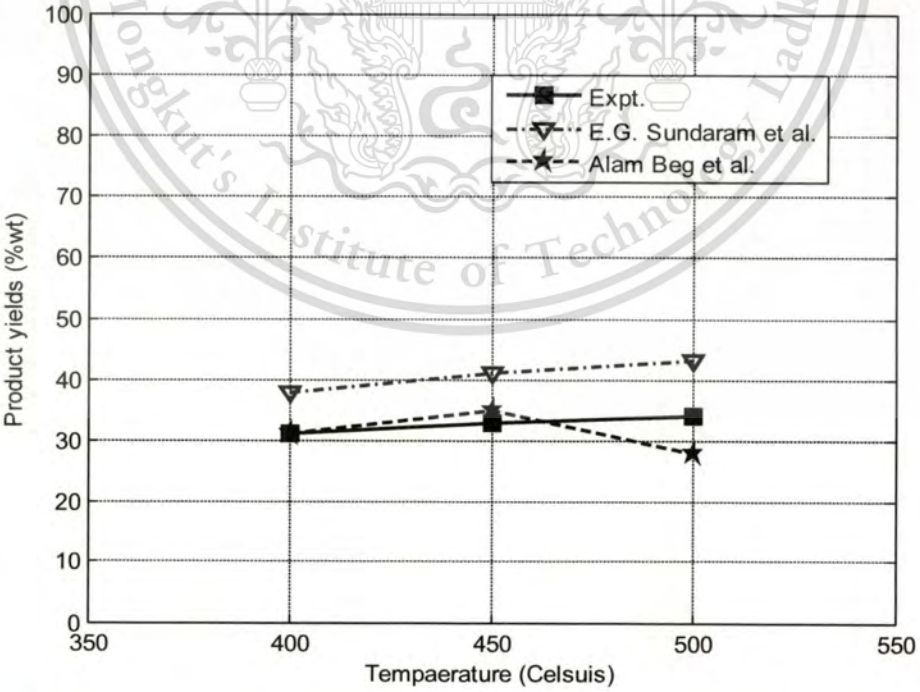


Fig. 5.18. The comparison of liquid product yields of this system with other research works.

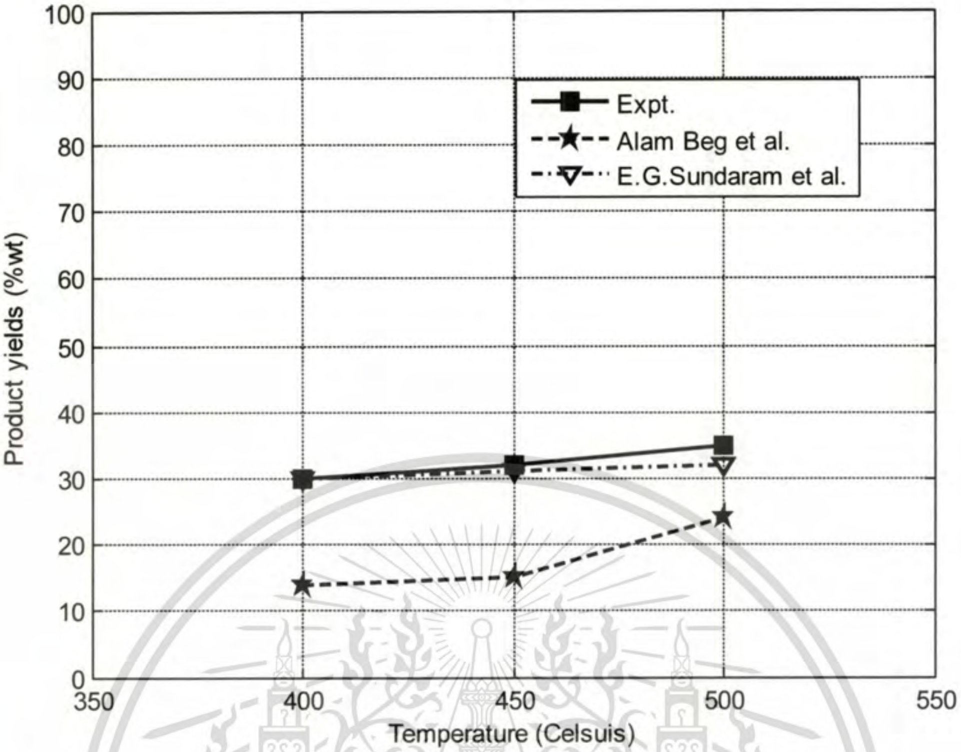


Fig. 5.19. The comparison of gas product yields of this system with other research works.

Table 5.8 The proportions of product yields from the carbonization process at three heating temperatures with 3,500 kg of coconut shells and 10-hour operating time each.

Product yields	400°C	450°C	500°C
Coconut charcoal	720 kg	680 kg	650 kg
Wood vinegar, Bio-liquid	150 liters	180 liters	200 liters
Gases	~ 570 m^3	~ 650 m^3	~ 700 m^3

Fig. 5.20. Coconut shell charcoal yields from the carbonization process.

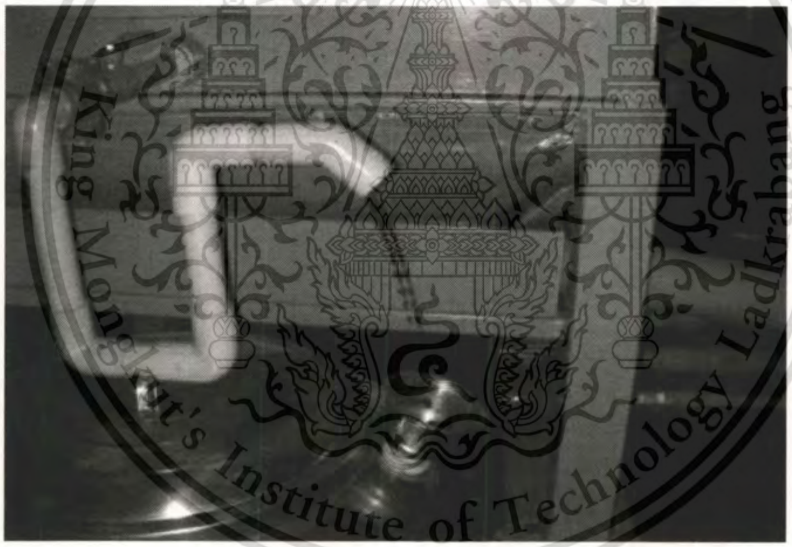


Fig. 5.21. The vinegar (liquid) yields from the wood vinegar condensation unit.

Table 5.8 summarizes the proportions of the product yields from the carbonization system using 3,500 kg of coconut shells with 10-hour operating time at three different heating temperatures. Figure. 5.20 is the image of the charcoal output yields which appear shiny when broken and are of low electrical resistance. Figure. 5.21 is the photograph of brown-black wood vinegar yields. Fuel gas yields from the carbonization were supplied to the engine-generator system. The electrical energy of approximately 10 kW was produced by the engine-generator system, which is sufficient to run the electrical system of the carbonization system.

Chapter 6

Conclusion and Discussion

6.1 Conclusion

The experimental results of the pilot scale continuous carbonization system of biomass using microwave heating technology suggest the potential of the proposed system which operates more smoothly with less production time required. The internal temperature of the proposed reactor can be not only fully controlled but also easy to adjust to satisfy diverse process conditions. Of the obtained product yields, charcoal can substitute fossil fuels, wood vinegar can be used in households and agricultural sectors as insecticides, and fuel gas is to run the engine-generator system to generate electricity to power the electrical system without the need for investment in the electrical grids, thus suitable for remote areas without the power grids. The application of this novel continuous microwave biomass carbonization system to produce renewable energy would considerably benefit the country economically and socially in general and environmentally in particular due mainly to its lower CO_2 emission. Notwithstanding, with a much larger system, the surplus electrical energy from the larger scale carbonization system could then be resold, thereby generating incomes for the community.

6.2 Discussion

As Thailand produces a lot of biomass waste each year, the implementation of the biomass carbonizer in different parts of the country is feasible and carries a high success rate. For instance, the Tarad Thai wholesale fresh market in Pathumtani province produces 80 tons/day of biomass waste, the quantity of which could be transformed into 10-20 tons/day of charcoal, 15 tons/day of wood vinegar and 100 – 150 kW of electricity. In addition, many agricultural areas in the provinces could benefit from installation of this proposed system. Currently, Thailand produces approximately 61 million tons of biomass waste annually; as a result, biomass waste should be better utilized by adding value to it or by transforming it into fuels or energy. Moreover, products from biomass waste reduce dependence on oil and coal import and transportation costs if the products are locally produced and consumed. As the biomass conversion technology is suitable for available biomass resources of particular areas, it is of great benefit to the local economy and the whole nation in the long run.

6.3 Comparison of the novel technology and the conventional method

The proposed carbonization system has many advantages over the conventional coal kiln method as follows:

- The novel system is more stable as it allows for control of temperature and air flow rate of carbonization.
- The novel system is applicable to all kinds of biomass waste and agricultural waste for production of bio-fuels, charcoal, wood vinegar and fuel gases, the last of which can be used in internal combustion engines, for electricity production and in the drying process.
- The proposed system is inexpensive to construct. In addition, as a heat source in the households and industrial sector, charcoal products from the novel system can substitute petroleum-based fossil oils and fuel gases.
- The system is ecologically and economically beneficial to the agricultural industry and many plantations as unwanted biomass waste can be turned into biofuels and thereby bring in supplementary incomes.

6.4 Indicator of innovation of this research

The prototype system under study has utilized the biomass thermochemical conversion technology, which is normally employed to convert agricultural biomass waste into bio-fuels, i.e., solid (charcoal), liquid (bio-liquid, wood vinegar, pyroligneous acid), and fuel gas [38-40]. The technology is not much different from the charcoal production process used by most rural villagers whereby woods are burned inside a traditional mound kiln or brick kiln. However, with the traditional kiln it is very difficult, if not impossible, to control the quality of charcoal and wood vinegar yields take a long time to process. Moreover, uncondensed gas is released into atmosphere. This research project intends to solve the problems of variable quality of charcoal and wood vinegar and to utilize the uncondensed gas as a fuel in the internal combustion engines or in the electrical production. Therefore, biomass waste and agricultural waste processed by the proposed system would bring a lot of benefits to the economy, society and environment [41-43].

6.5 Commercial Utilization

The researcher has planned to collaborate with Prommark Co., Ltd. to install this proposed system to produce bio-fuels on a commercial scale in the province of Chonburi, east of Bangkok.

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Appendix

A. The plan of the pilot-scale continuous biomass carbonization system using multi- feed microwave heating.

B. The electrical diagram of the continuous biomass carbonization system using multi-feed microwave heating.

C. The components of the pilot-scale continuous biomass carbonization system using multi-feed microwave heating.

Appendix A

The plan of a pilot-scale continuous biomass carbonization system using multi- feed microwave heating.

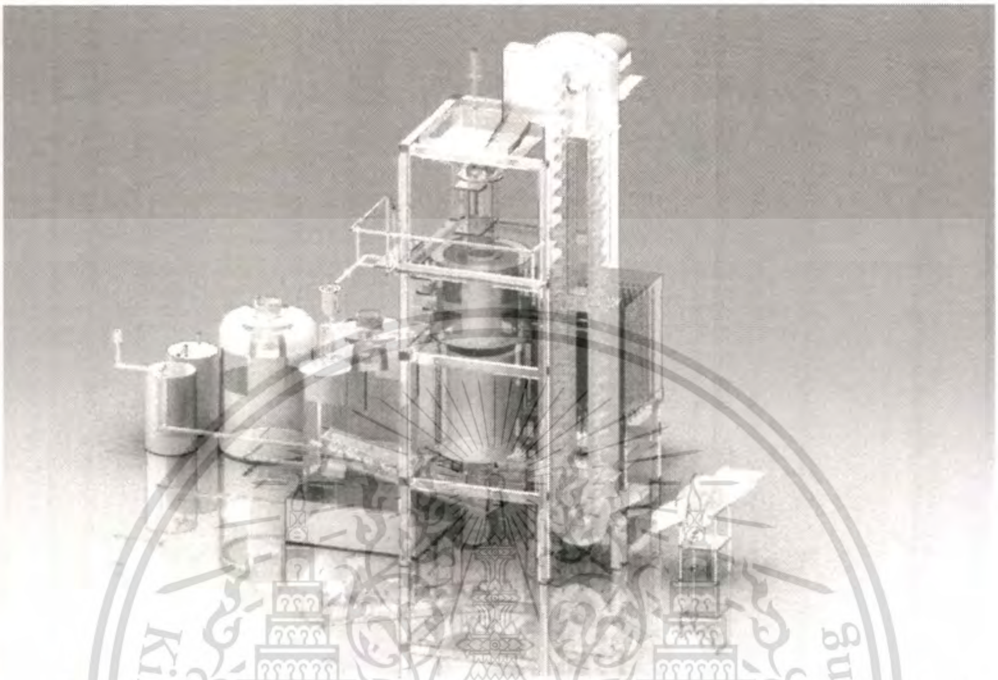


Fig. a.1. The plan of a pilot-scale continuous biomass carbonization system using multi- feed microwave heating (1).

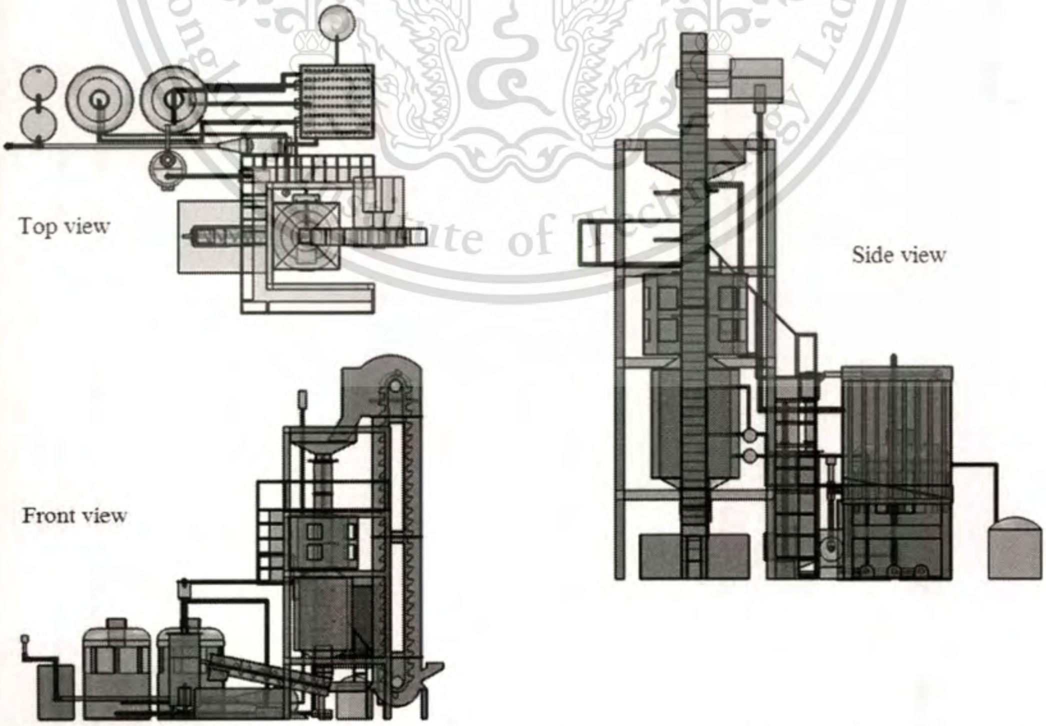


Fig. a.2. The plan of a pilot-scale continuous biomass carbonization system using multi- feed microwave heating (2).

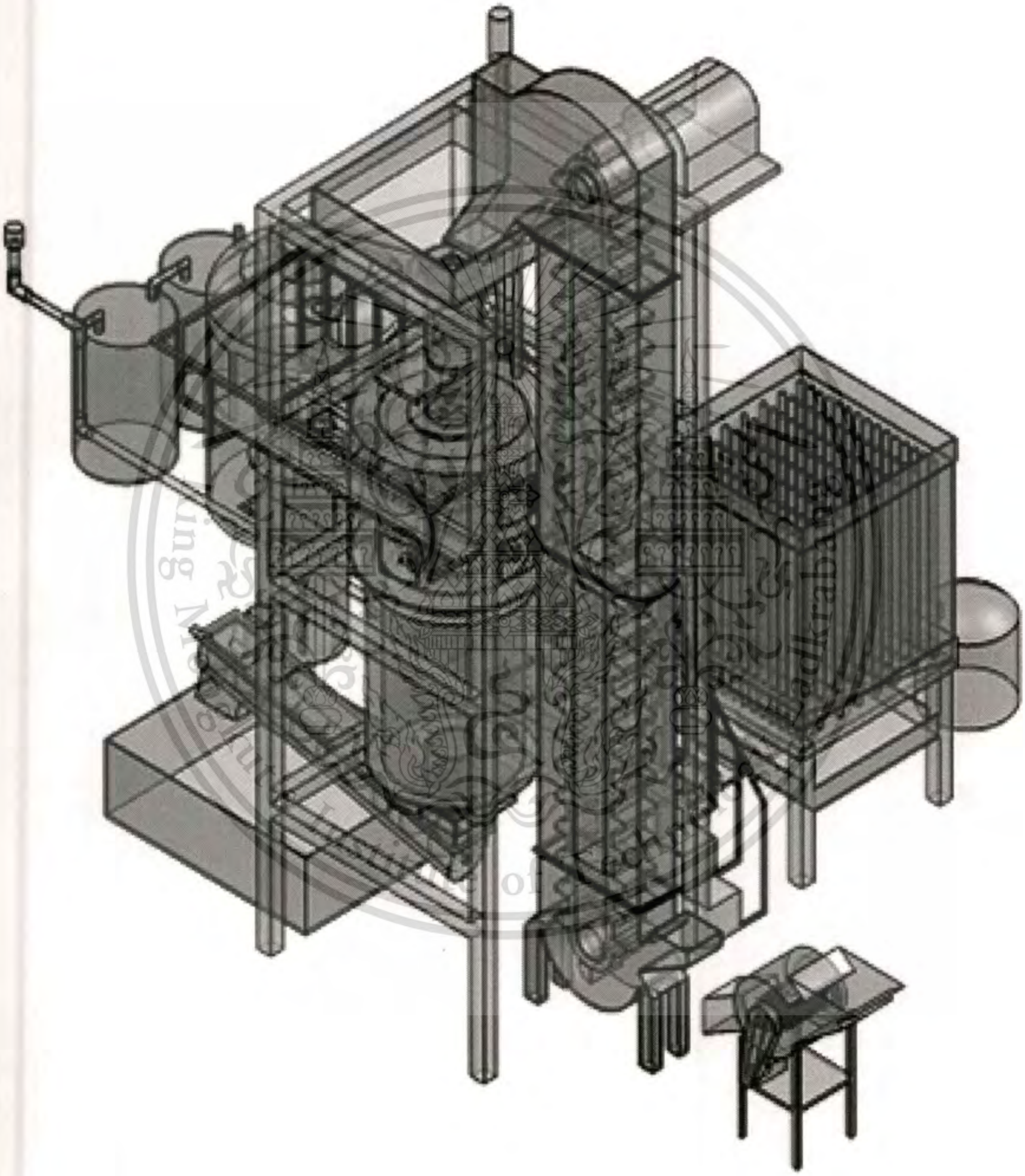


Fig. a.3. The plan of a pilot-scale continuous biomass carbonization system using multi- feed microwave heating (3).

Appendix B

The electrical diagram a continuous biomass carbonization system using multi-feed microwave heating.

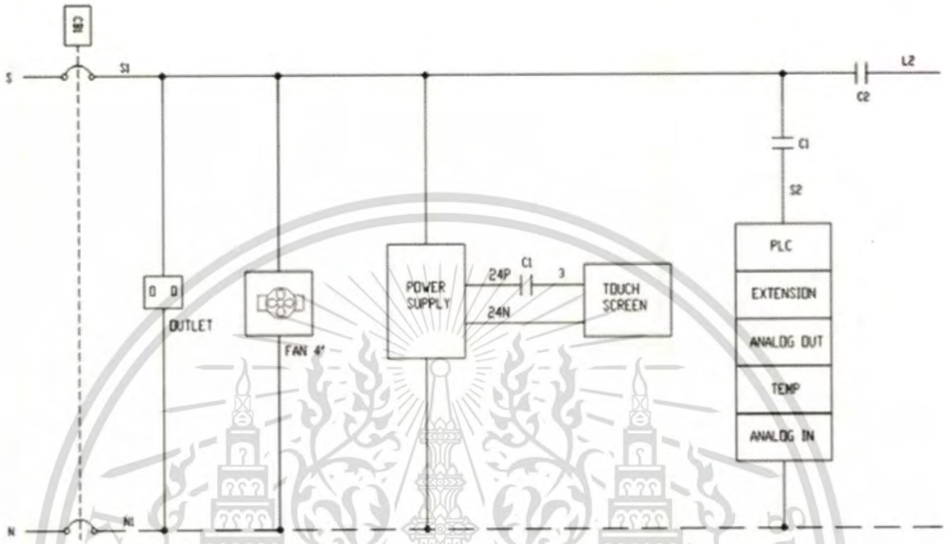


Fig. b.1. Diagram of a operating system control.

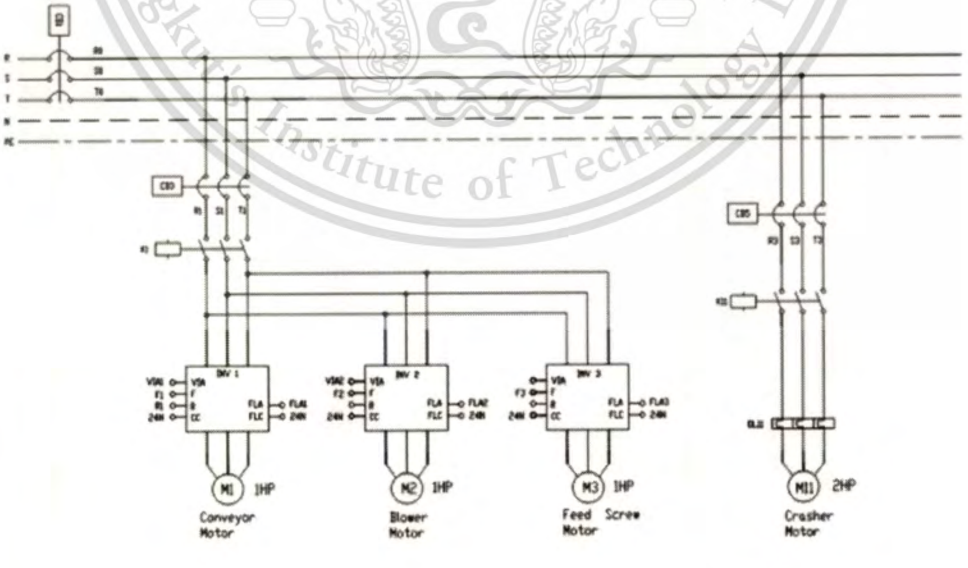


Fig. b.2. Diagram of a inverter control.

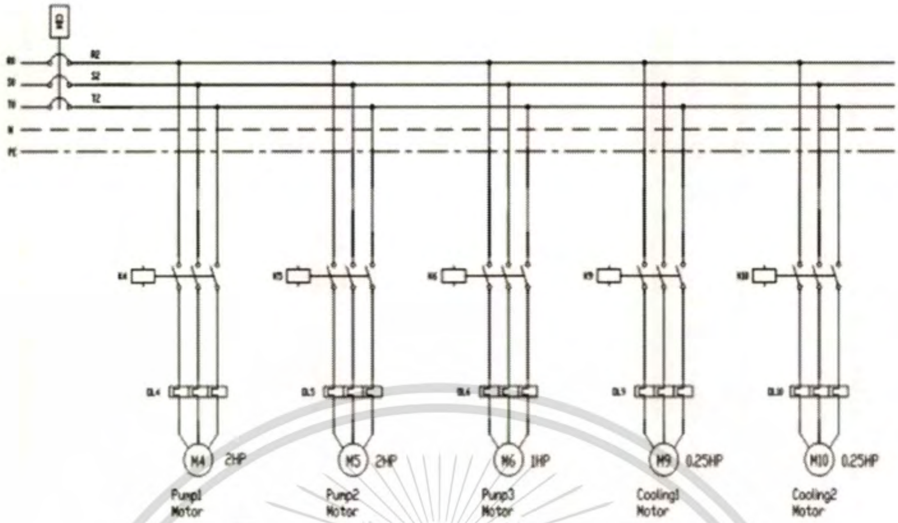


Fig. b.3. Diagram of the motors control.

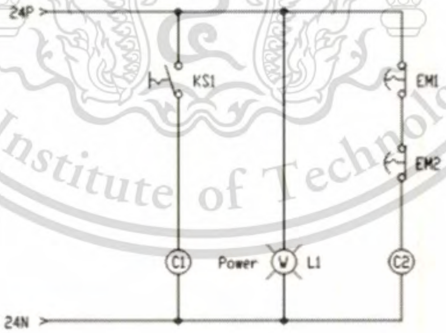


Fig. b.4. Diagram of a protection system.

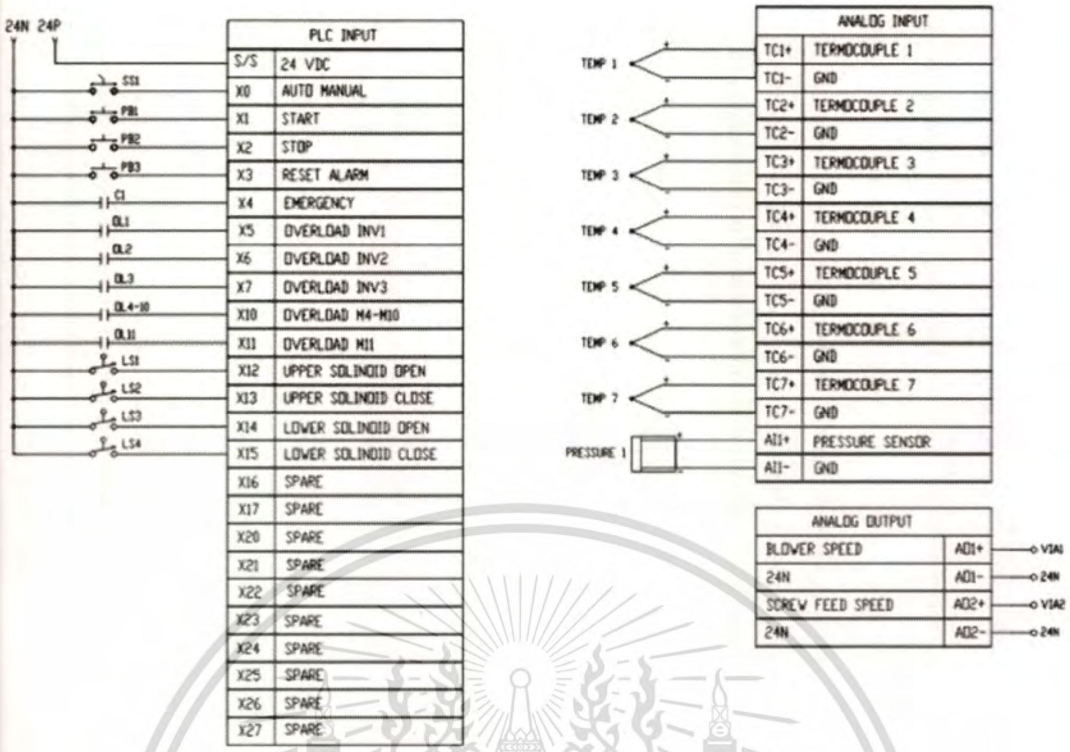


Fig. b.5. Diagram of the PLC inputs.

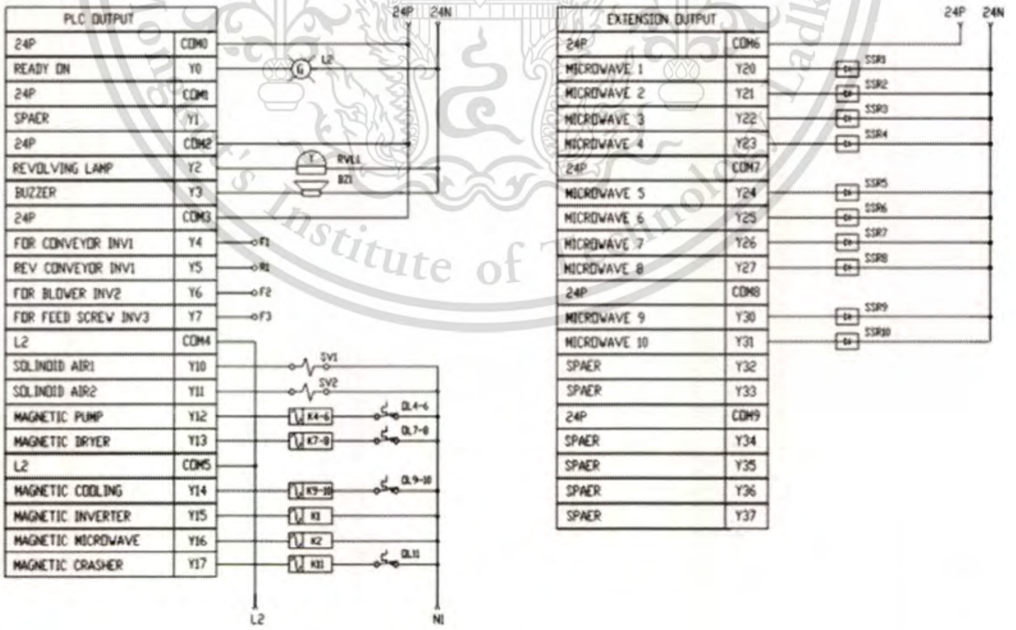


Fig. b.6. Diagram of the PLC outputs.

Appendix c

The components of a pilot-scale continuous biomass carbonization system using multi-feed microwave heating

Fig. c.1. The continuous biomass carbonization plant (front view).

Fig. c.2. The continuous biomass carbonization plant (side view).

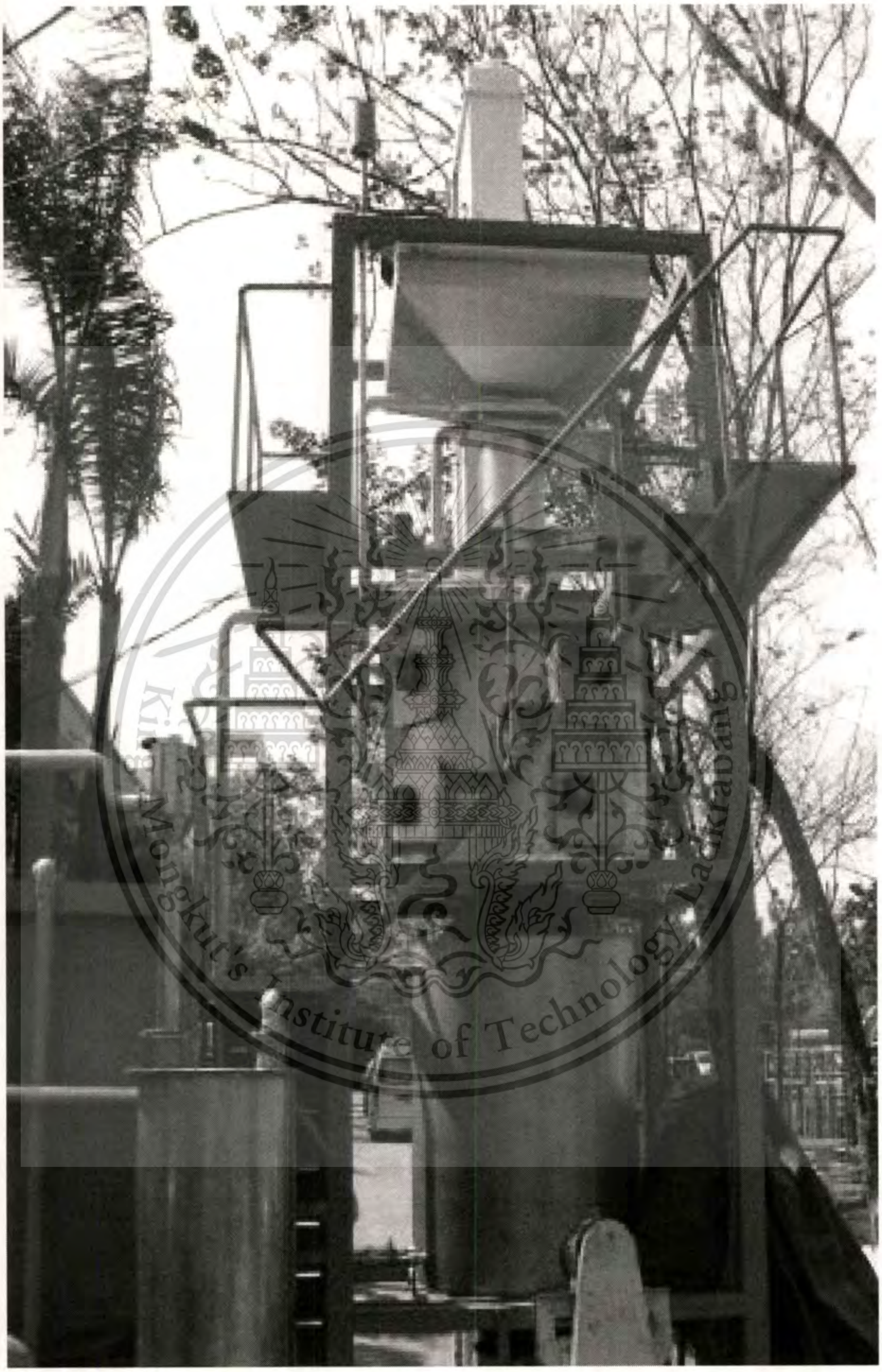


Fig. c.3. The continuous biomass carbonization plant (back view).

Fig. c.4. The cooling tower (yellow).

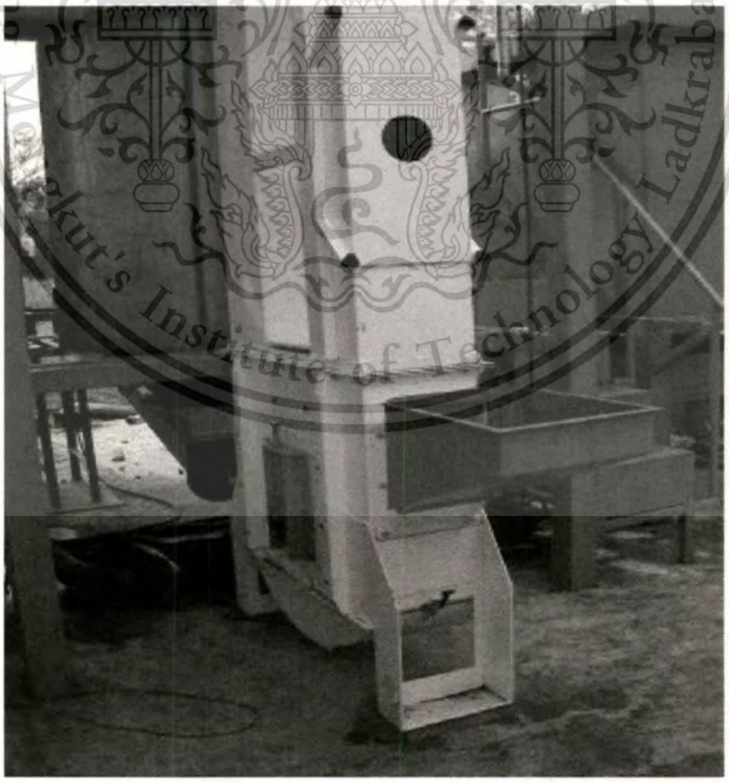


Fig. c.5. The bucket elevator.

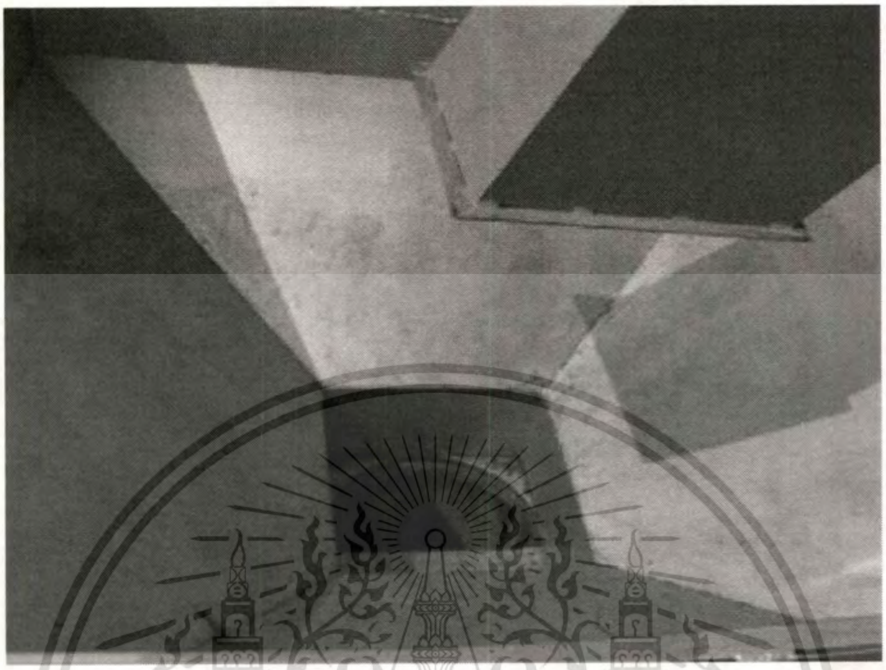


Fig. c.6. The hopper.

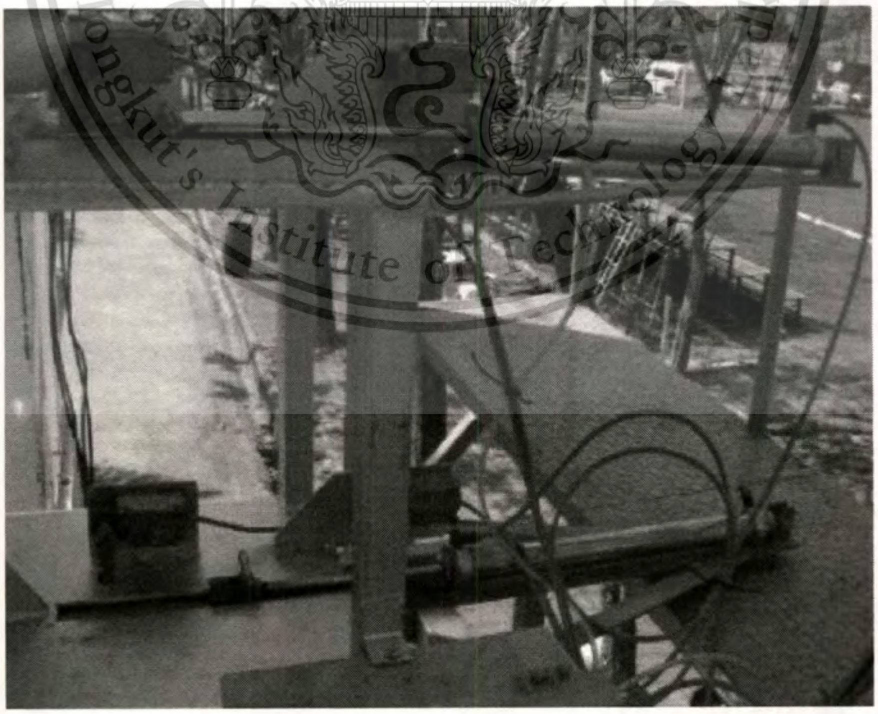


Fig. c.7. The pneumatic stainless steel trays.

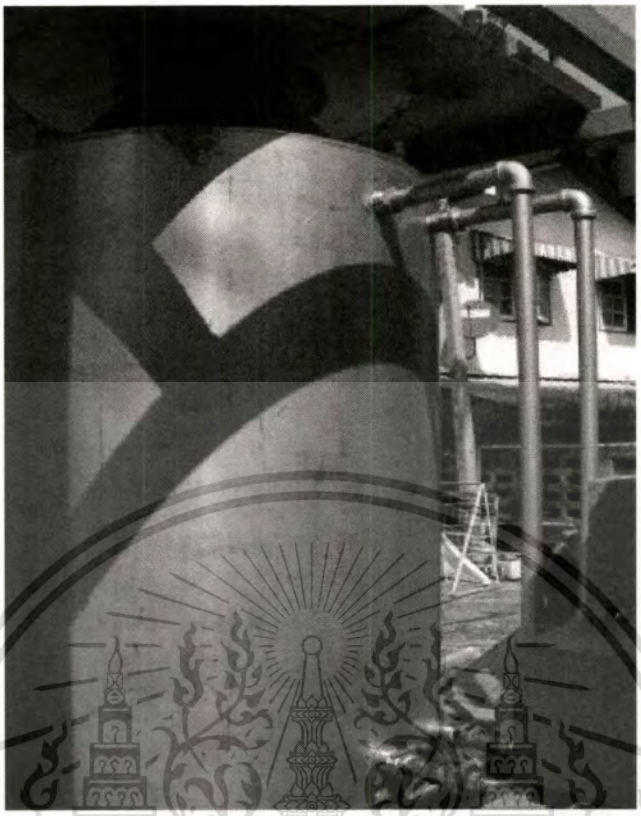


Fig. c.8. The charcoal temperature reduction unit.

Fig. c.9. The charcoal temperature reduction unit (bottom side).

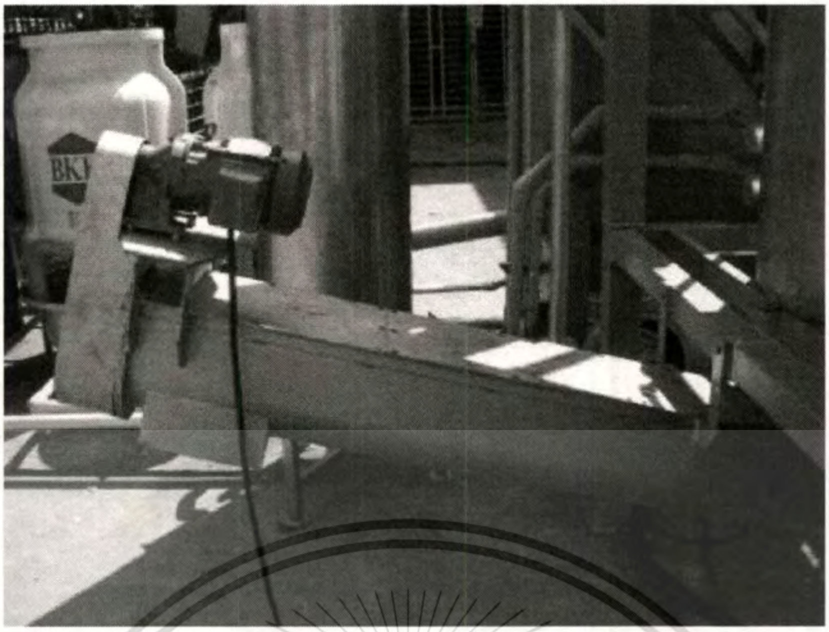


Fig. c.10. The screw conveyer.

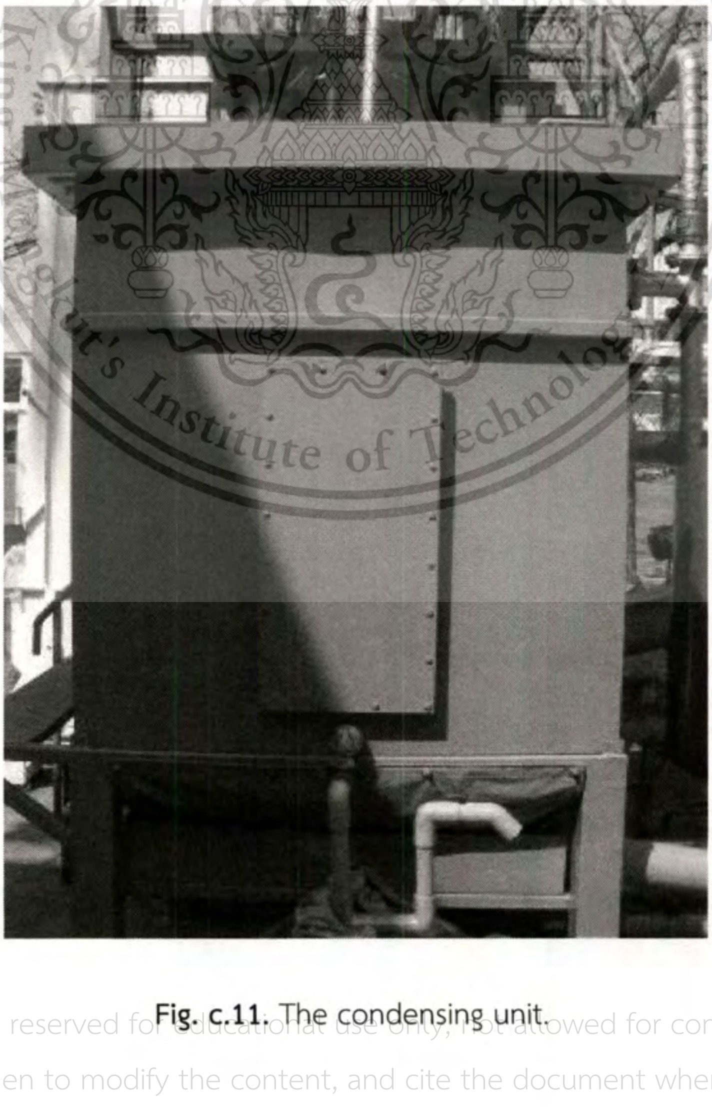


Fig. c.11. The condensing unit.

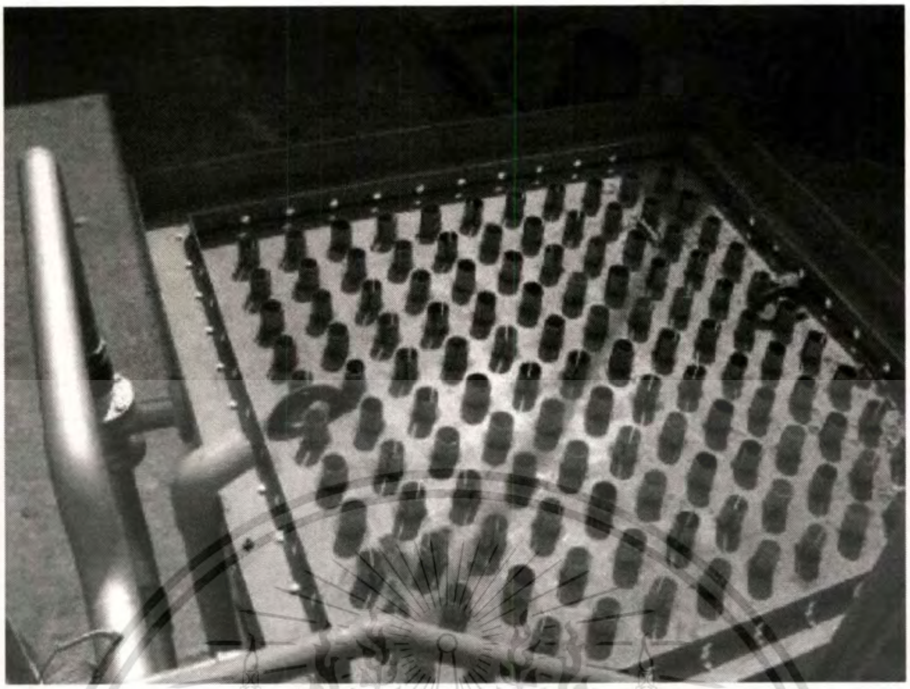


Fig. c.12. The condensing unit (top view)

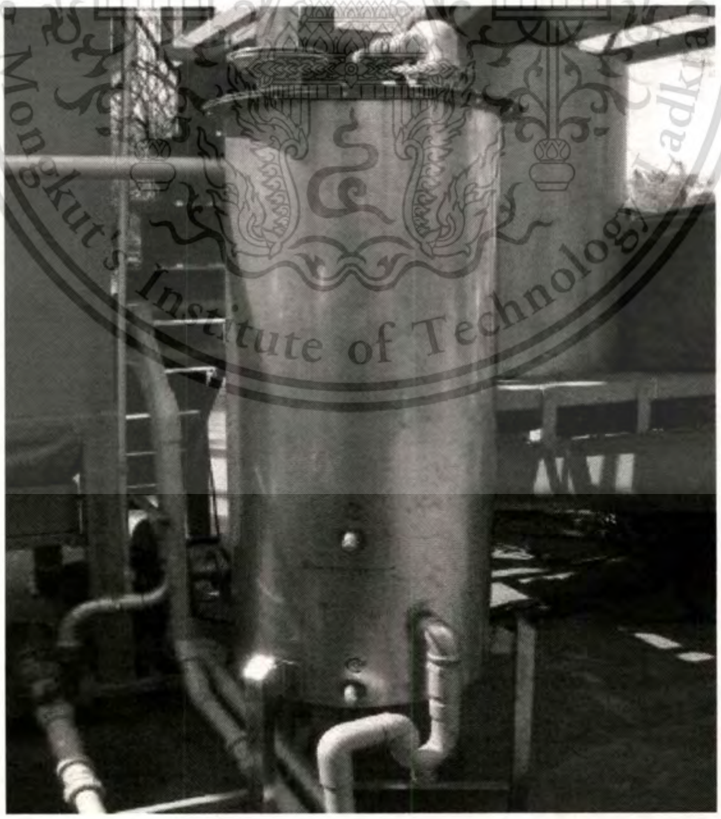


Fig. c.13. The gas treatment unit.

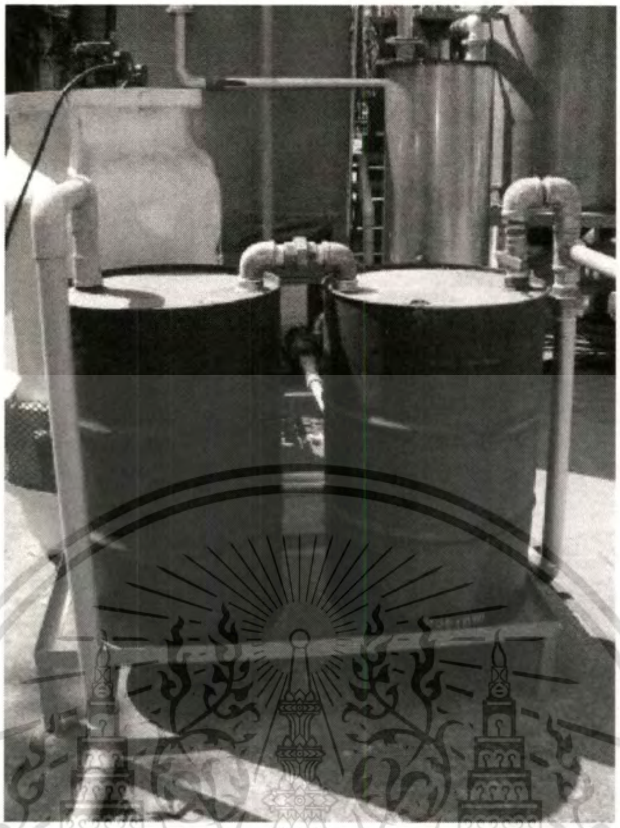
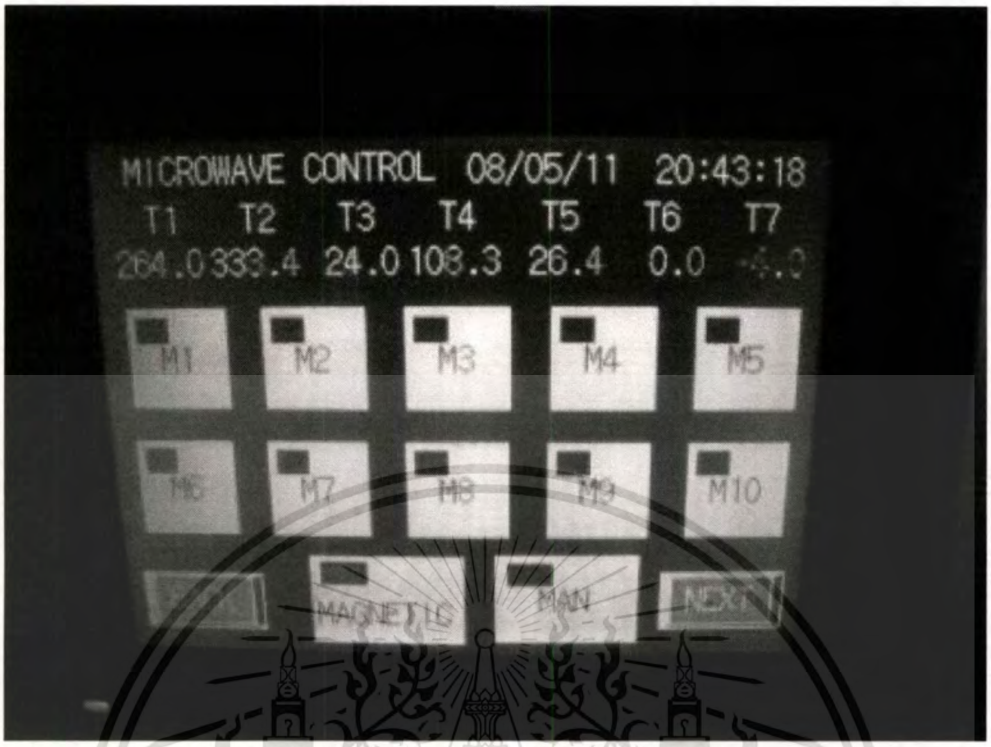


Fig. c.14. The gas tanks.

Fig. c.15. The engine – generator system.

Fig. c.16. The operating display unit.

Fig. c.17. The PLC control unit.



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MICROWAVE CONTROL  08/05/11  20:43:18
 T1     T2     T3     T4     T5     T6     T7
264.0 333.4  24.0 108.3  26.4   0.0   -4.0
```

Fig. c.18. The operating display.

Fig. c.19. Biomass feeding.

Fig. c.20. The coconut shell wood vinegar sample.

List of publications

2009 **Poomyos Payakkawan**, Kitdakorn Klomkarn and Pitikhate Sooraksa “ Dual-line PID Controller based on PSO for Speed Control of DC motors ” 9th International Symposium on Communication and Information Technology (ISCIT 2009), pp. 134–139, Incheon, Korea, 28-30 September 2009.

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2012 Suwilai Areejit, **Poomyos Payakkawan**, Anurak Jansri, Kitdakorn Klomkarn, Hisayuki Aoyama and Pitikhate Sooraksa, “Chaotic Application for Industrial Microwave Heating System without Mode-Stirring Mechanism” International Conference on Microwave and Millimeter Wave Technology (ICMMT2012), Vols 5, pp. 1-3, Shenzhen, China, 5-8 May 2012.

2012 **Poomyos Payakkawan**, Suwilai Areejit, Anurak Jansri, Kitdakorn Klomkarn, Hisayuki Aoyama and Pitikhate Sooraksa, “The Design and Implementation of Continuous Microwave Biomass Carbonization System”, International Conference on Microwave and Millimeter Wave Technology (ICMMT2012), Vols 5, pp. 1-4, Shenzhen, China, 5-8 May 2012.

2013 **Poomyos Payakkawan**, Suwilai Areejit, and Pitikhate Sooraksa “Novel Microwave Carbonization System for Coconut Shells”, Advanced Materials Research, Trans Tech Publications, Switzerland, Vols. 750-752 (2013) pp. 1539-1544.

2014 **Poomyos Payakkawan**, Suwilai Areejit, and Pitikhate Sooraksa “The Design and Fabrication and operation of Continuous Microwave Biomass Carbonization System”, Renewable Energy : An International Journal, Elservier, Vols. 66 (2014) pp. 49-55.

Author biography

Mr. Poomyos Payakkawan was born in 1971 at the province of Samutsongkram. He received the B.Eng degree from the Department of Information Engineering, King Mongkut's Institute of Technology Ladkrabang, in 2001, and the M. Eng degree from the Department of Control and Instrumentation Engineering, King Mongkut's University of Technology Thonburi, in 2007. In addition, he was given a valuable opportunity as a research student to work with and learn under the Biomass to Liquid (BTL) project at Karlsruher Institute of Technology, Germany, from April to June 2010 with the financial support from the National Innovation Agency (NIA), Ministry of Science and Technology of Thailand. In 2013, he completed his doctoral degree in Electrical Engineering from the Faculty of Engineering, KMITL. His research interests are energy conversion, control application, process control, waste into energy, pyrolysis/gasification process control, renewable energy and microwave heating technology. Currently, he is working at Prommark Co., Ltd.