Numerical Approach to Wood Pyrolysis in Considering Heat Transfer in Reactor Chamber

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Abstract. Pyrolysis is the decomposition process of solid biomass into gas, tar and charcoal through thermochemical methods. The composition of biomass consists of cellulose hemicellulose and lignin, which each will decompose at different temperatures. Currently pyrolysis has again become an important topic to be discussed. Many researchers make and install the pyrolysis reactor to convert biomass waste into clean energy hardware that can be used to help supply energy that has a crisis. Additionally the clean energy derived from biomass waste is a renewable energy, in addition to abundant source also reduce exhaust emissions of fossil energy that causes global warming. Pyrolysis is a method that has long been known by humans, but until now little is known about the phenomenon of the pyrolysis process that occurs in the reactor. One of the Pyrolysis’s phenomena is the heat transfer process from the temperature of the heat source in the reactor and heat the solid waste of biomass. The solid waste of biomass question in this research is rubber wood obtained from one of the company’s home furnishings. Therefore, this study aimed to describe the process of heat transfer in the reactor during the process. ANSYS software was prepared to make the simulation of heat transfer phenomena at the pyrolysis reactor. That's the numerical calculation carried out for 1200 seconds. Comparison of temperature performed at T1, T2 and T3 to ensure that thermal conductivity is calculated by numerical accordance with experimental data. The distribution of temperature in the reactor chamber specifies the picture that excellent heat conduction effect of the wood near or attached to wooden components, cellulose, hemicellulose and lignin down into gas.

1. Introduction

1.1. Biomass as an Energy Source
Development of renewable energy today is still relatively low, but has an important role in contributing to the electric energy supply in Indonesia. Some renewable energy comes from solar energy, wind energy (wind), biomass, hydroelectric power (hydropower) and geothermal energy. According to the Renewable Energy Market Assessment Report: Indonesia [1], that the Presidential Decree No. 5 decided a government program to increase the production of renewable energy from 7 percent to 15 percent in fraction of total energy production by 2025. The government
should positively advance the installation of renewable energy power plants in order to achieve the target that the electric power by renewable energy reaches around 90 GW by 2025. Indonesia has a source of renewable energy that is large, as shown in Table 1.1. It means that there is big potential in Indonesia to develop carbon-neutral energy that can moderate climate change and prevent further global warming.

| No. | Energy Source | Installed capacity (MW) | Recourse Potential (MW) | Undeveloped Potential (%) |
|-----|---------------|-------------------------|--------------------------|---------------------------|
| 1   | Hydropower    | 5,264                   | 75,670                   | 94                        |
| 2   | Geothermal    | 1,052                   | 27,510                   | 96                        |
| 3   | Biomass       | 445                     | 49,810                   | 99                        |
| 4   | Solar         | 12                      | 4.8kWh/m2/day            | -                         |
| 5   | Wind          | 1                       | 9,190                    | 99                        |
| 6   | Ocean         | 0                       | 35                       | 100                       |

Biomass is one of the energy resources, especially wood waste used for cooking in rural households. Besides, it is also used for a raw material in the energy industry and commercial sector. In the processing industry and forest plantations, biomass is used to generate not only thermal energy (steam or heat), but also electricity.

1.2. Research Objective

Indonesia has big sources of biomass energy; it is shown in table 1.1. How can it use high potential biomass for energy, especially wood waste? There are several ways of energy conversion of wood waste. These are as follows:

1. Direct burning for heat
2. Liquids fuel production
3. Gasification of biomass

Direct burning of wood has been used as the easiest way of energy conversion since ancient era. Technology to produce liquid fuel and gas fuel from wood is positively developed in the recent few decades. The main technology is pyrolysis. This study aims to utilize the wood waste into bio gas through the pyrolysis path. Many peoples have known pyrolysis method to convert waste wood into charcoal tar and gas, and many researchers have investigated the pyrolysis of biomass, but there is still little research that examines the phenomenon that occurs in the pyrolysis chamber. Therefore the main objective of this study was to describe the phenomenon of pyrolysis based on the of heat conduction. A software prepared to resolve this problem. In the next section, we will review the wood pyrolysis researches.

1.3. Review on Previous Woods Pyrolysis Researches

All the organic materials have the potential converted into energy. In general, there are two paths in biomass conversion as shown in Figure 1.2, they are the biochemical and thermochemical processes [2].
Thermochemical conversion is the decomposition process of solid biomass molecules transformed into liquid and gaseous materials under heat. For example, wood pyrolysis is one of the thermochemical conversion processes. Pyrolysis is a process of molecular decomposition of biomass of heat without air supply or below atmospheric pressure to produce charcoal (solid), bio-oil (liquid) and gas.

Homma al. have carried out the wood pyrolysis in pre-vacuum chamber. The study’s purpose is to utilize biomass waste, especially wood waste, where the sources are abundant. Wood waste converted to bio gas through the thermochemical path, the name is pyrolysis. The biogas yield from the pyrolysis method used for generator fuel to generate electricity in rural area. This work aims to solve the global issue in the global framework. The global issue are climate change, global warming and energy crisis. Where the global issue impacted by the many aspects, the biggest aspect of them are gas emission from the fossil fuel [3]

1.3.1. Numerical Analysis of pyrolysis

The heat released during the pyrolysis process takes place and is measured using a calorimeter that burned polymer can be measured accurately. The data were measured using these tools is the heat release rate, peak rate of heating and ignition timing. Modelling of heat release was measured using a cone calorimeter has not been extensively studied in char formation in polymers. To determine the heat release rate with the help finite element one dimension with the help of software COMSOL Multiphysics. This model considers the phenomenon of heat and mass transportations lasted the entire thickness of the polymer and char [4].

Homma al. also have been carried out the numerical analysis to wood pyrolysis, the purpose of the research is to describe the pyrolysis phenomena at considering heat and mass transfer and chemical reaction. The large wood pyrolysis in the pre vacuum chamber is too complicated. The two-step general reaction model was purposed for the numerical analysis [5]

1.4. Numeric Analysis Model to Be Developed

To understand the pyrolysis process in the pilot plant developed in this study, numerical analysis approach is most effective. However, as mentioned above, numerical analysis of pyrolysis process has not been established yet. Essentially, pyrolysis process in a large reactor chamber has not been analyzed yet. In the reactor chamber of the pilot plant, big temperature gradient exists as shown by the experiments. Therefore, the numerical analysis model to be developed in this study must satisfy the following requirements

1. Setting of the pre - vacuum condition of the reactor chamber is possible
2. Temperature analysis in the chamber is possible
3. The temperature gradient in wood piece can be analyzed
4. Wood model is constructed from three main components, cellulose, hemicelluloses, and lignin

2. Research Method
In this chapter, experimental work done by the same laboratory is outlined briefly. Then, considering experimental apparatus and obtained results, a numerical analysis method is developed. In this chapter, the research method is described in details.

2.1. Feedstock of pyrolysis
Pyrolysis feedstock and furnace fuel used in the experiment were rubber wood waste and were supplied by one furniture company in Medan, Indonesia. Now, in the world, many companies fabricate furniture using rubber wood. In North Sumatra, huge rubber plantations are developed and after harvesting latex, rubber timbers are processed and used to produce furniture. During the production, small timber pieces come out as wastes. In Medan area, rubber timber wastes can be supplied sustainable.

2.2. Experimental Equipment
The equipment used in the experiment consists of a furnace, reactor chamber, three points of thermocouple inside reactor chamber, the pressure gauge to hold the gas before the released reservoir tank for the gas yield.

2.3. Temperature Measurement
Measurement of temperature in the experiment was done by using thermocouples placed in three positions, the chamber bottom and top of the chamber, and the surface of the outer chamber as shown in Figure 2.1. By this way, the temperature-time evolution can be measured precisely. In the figure, thermocouple position near the chamber top is precisely shown in the exact comparison between experimental data and numerical analysis results.

2.4. Experimental Method
The experiment is carried out through several steps. The steps are:
1. Charge five kg of dried rubber wood pieces into chamber
2. Fill heat exchanger tank in the tar trap with water and makes water circulation during the experiment
3. Fill the tank in the CO2 absorber with water
4. All components of the equipment including the tanks and pipes are vacuumed with a vacuum pump

![Figure 2. Temperature measurement](image-url)
5. Close a valve installed before the tar trap in order to control the required pressure conditions in the chamber
6. Start the ignition of wood fuels in the furnace for an experiment beginning.
7. Monitor the pressure in the chamber and take note of the change of pressure at a constant time interval.
8. Temperatures Three positions are monitored and recorded at a constant time interval.
9. When the pressure reaches a prescribed value, 0.2 MPa, the valve is opened to release the gas in the chamber into the gas reservoir and to keep the chamber pressure at the specified value.
10. After the completion of the experiment, the pyrolysis yields, charcoal, tar, and gas are measured. The Gas product is used for engine generator to generate electricity.

2.5. Measured results
The measured results have been discussed just on temperature per time based on experiments in the laboratory. The temperature was carried out at the three positions for two different specified pressure conditions. Pressure was also monitored by a pressure gage installed before the tar trap. The measured results have been discussed just on temperature per time based on experiments in the laboratory. The temperature was carried out at the three positions for two different specified pressure conditions.

2.5.1. Temperature
T1 is the temperature at the chamber bottom, T2, at the chamber top, and T3, at the surface of the upper chamber, respectively. The thermocouples are connected to a digital thermometer and the temperatures at the three positions are recorded at a constant time interval from the beginning to the end of the experiment. In Figure 2.2, the measured temperatures of the pyrolysis process at three positions are plotted. When the temperature T1 reaches 671 K at 1320 seconds, the temperature suddenly drops and decreases to 449 K at 1380 seconds. At the same time when the temperature drops, the chamber pressure reaches 0.2 MPa and the valve is open to keep the chamber pressure 0.2 MPa.

![Figure 3. Pyrolysis temperature process](image)

2.6. Numerical Analysis Method
In this study, two softwares are used to simulate thermal conduction in the reactor chamber. To construct an axisymmetric model of the reactor chamber used for the experiments, stone tools software AUTO CAD is used. In Figure 2.3, shows an example of the reactor chamber model. The model file is exported to the IGES file for ANSYS Multiphysics 13.0. The red circle in figure a is a reactor chamber actually, b is a 3d design of reactor chamber using Auto CAD, c is a simple reactor chamber design become 2d asymmetric case as suitable to the asymmetric formula 2.1. The red quart of the circle is air ambient considered.

\[-k \frac{\partial T}{\partial r} = h(T - T_\infty)\]  \hspace{1cm} \text{..........................(2.1)}
ANSYS Multiphysics 13.0 is one of comprehensive Finite Element Method (FEM) software to analyze the structure, heat, fluid mechanics, and electromagnetic problems. In this study, ANSYS Multiphysics are used to analyze heat transfer phenomena inside the chamber. IGES files imported from AUTO CAD Work can be seen on ANSYS preprocessor display. In the ANSYS preprocessor, all parameters necessary for analysis are defined as follows:

a. Type of elements
b. Material Model
c. Heat loads and boundary conditions

The physical properties of materials greatly influence the results of the reaction occurring inside the chamber. Tables 2.1 are four materials used in numerical analysis of heat transfer in the reactor chamber as follows:

1. Stainless steel for a reactor chamber, SUS 404, martensitic stainless steel
2. Woods for feedstock, dried rubber timers charged in the reactor chamber
3. Ambient air
4. Air inside chamber vacuumed to 0.02 MPa. It is done to reduce the air inside the chamber is less

| No. | Material Properties       | k, W/mm K         | Cp J/Kg.K | Density Kg/mm³ |
|-----|---------------------------|-------------------|-----------|---------------|
| 1   | Stainless Steel           | 5.20E-02 at 304 K | 4.00E+02  | 8.0E-06       |
|     |                            | 5.40E-02 at 1000 K|           |               |
| 2   | Wood                      | 1.37E-04          |           | 4.0E-07       |
|     |                            |                   | 1.250 at 304 K |               |
|     |                            |                   | 4.647 at 1000 K|              |
| 3   | Air ambient                | 4.00E-05 at 304 K | 1.007     | 1.0E-09       |
|     | Air inside chamber         | 10.0E-5 at 1000 K |           |               |
|     | (0.02MPa)                 |                   |           | 717           |
|     |                            |                   |           | 2.0E-10       |

Properties of air inside the chamber are same as those of ambient air except density. The thermal properties of air is almost independent of pressure assumed. In the air inside the chamber, specific heat under constant volume should be used.
2.6.1. Heating condition of wood stove furnace
In the experiment, the reactor chamber was heated by the wood stove furnace. The chamber was partly immersed into the furnace and the immersed part of the chamber was directly heated by the combustion flame of wood. In this study, we could not measure the flame temperature. It is postulated that heating of the chamber by wood stove furnace can be represented by the temperature at the chamber bottom measured in the experiment.

3. Result and Discussion

3.1. Synoptic View of Temperature
Figure 3.1 shows the synoptic view of temperature contours inside and outside the reactor chamber at 1200 seconds after heating chamber. Ambient air near the furnace is heated up to 600 K, but near the chamber top the temperature is around 310 K. Inside the chamber, wood piece temperature is still low except near wall of the chamber that is heated up to 600 K. According to the experimental results, pyrolysis of wood has started from 480 to 540 seconds after experiment starts [3]. Therefore, at 1200 seconds, volatiles or gases have been emitted into the reactor chamber. Regardless, this fact, the numerical computation was done until 1200 seconds. In this numerical analysis, heat transfer is analyzed using solid elements, even in ambient air and chamber air. Namely, heat convection and radiation effects are neglected in the analysis. We suppose that convection and radiation does not affect significantly temperature inside the chamber, because the chamber is in vacuum and high temperature part of a chamber inside is covered by wood pieces. Slightly different from the research that's been published in Figure 3.2 [5], numerical calculations carried out until the time reaches 1304 seconds, where the lowest temperature was 299 K and the highest temperature reached 661 K. Analysis of numeric assessed on the basis of chemical reactions using ANSYS Fluent. Decomposition of the wooden components turn into steam to steam occurs after 890 seconds.

3.2. Comparison Temperature Process inside Chamber
Figure 3.2. a, b and c consecutive as comparison the temperature experimental data and numerical analysis results is made in. The red dot is measured temperature experiment during the pyrolysis process inside the chamber. The black line is the calculated temperature by this analysis. A heating load of the furnace is taken from the measured temperature at the chamber bottom. If the thermal

![Figure 5](image5.png)  
**Figure 5.** Temperature contour at 1200 second (20 minutes), calculated by ANSYS APDL. The lowest temperature is 304 K and the highest temperature reach 635 K.

![Figure 6](image6.png)  
**Figure 6.** Numerical analysis calculated by ANSYS Fluent, where the lowest temperature is 299 K and the highest temperature is 661 K.
conduction in the chamber bottom plate is very fast, both the temperature should agree with each other. As seen in the figure, before 1000 seconds, both results agree very well. We assume the heat flux from the chamber bottom plate into wood piece makes the difference between both the results. It can be seen that the numeric analysis used in this study is reasonable as far as this comparison is made.

Figure 7. Temperature comparison of the experimental data and the numerical calculation

3.3. Temperature Distribution at 1200 Seconds
Numerical Calculasi run for 1,200 seconds or as long as 20 minutes. It is based on data obtained experiments that have been done which indicates that at the time (t) is pyrolysis has begun. This assumption is justified by the increase in pressure in the chamber until it reaches 0.2 MPa. Where the pressure rise caused by wood components decompose cellulose, hemicellulose and lignin into gas. Furthermore, this phenomenon is described by a numerical calculation is shown in Figure 2.3, that the temperature distribution of the bottom has been mecapai 630.3 K and evenly up to the middle chamber. In this condition, all components of wood, cellulose, hemicellulose and lignin in direct contact with chamber wall has emitted due to the heat. In contrast to the temperature distribution in the middle and upper consecutively only reached 304 K to 320 K and timber position that is close to the chamber wall having a temperature which tend to be similar to the distribution of the temperature at the bottom of which is a 630.3 K timber position that is close to the chamber wall has a temperature which tend to be similar to the distribution of the temperature at the bottom of which is 630.3 K.
4. Conclusion
After the simulation to compare the working temperature at the points of measurement and temperature distribution inside chamber calculated, simulation results obtained are quite close to the experimental results that have been done. This shows that the heat transfer process that occurs in the reactor vessel was excellent.

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