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To cite this article: S Siahaan *et al* 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **308** 012047

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Development of secondary chamber for tar cracking—improvement of wood pyrolysis performance in pre-vacuum chamber

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Abstract. Energy crisis and global warming, in other words, climate change are critical topics discussed in various parts of the world. Global warming primarily result from too much emission of carbon dioxide (CO₂) in the atmosphere. To mitigate global warming, or climate change and improve electrification in rural areas, wood pyrolysis technology is developed in a laboratory scale, of which gases are directly applicable to the gas engine generator. Our laboratory has developed a prototype of wood pyrolysis plant with a pre-vacuum chamber. However, tar yield was around 40 wt% of feedstock. This research aims to reduce tar yield by secondary tar cracking. For the secondary tar cracking, a secondary pre-vacuum chamber is installed after primary pre-vacuum chamber. Gases generated in the primary pre-vacuum chamber are lead into the secondary chamber that is heated up to 1000 K. This paper reports performance of the secondary chamber for secondary tar cracking in homogeneous mode and heterogeneous mode with char.

1. Introduction

Today the energy crisis and global warming which lead to climate change are hot topics discussed in various parts of the world. The energy crisis has other two aspects, limited energy resources, and secure access to energy resources. Global warming is a phenomenon of the increase in the average temperature of the atmosphere, ocean, and land. Temperature of the earth is getting warmer at this time. Average global temperatures have risen by more than 1 degree Fahrenheit over the last century, with average warming of as much as 4 degrees Fahrenheit in some regions [1]. The largest contributing source of greenhouse gas is burning of fossil fuels emitting carbon dioxide [2]. Since the Industrial Revolution, annual CO₂ emissions from fuel combustion dramatically increased from near zero to almost 32 GtCO₂ in 2012 [3]. On the other hand, recently biomass is increasingly receiving large attention, because the biomass is one of renewable energy resources, and significant reduction of greenhouse gas emission is expected [4]. Primary energy consumption in the world will increase from 13,371 million tonnes of oil equivalent (Mtoe) in 2012 to 19,276 Mtoe in 2040 [5]. The energy crisis in South East Asia where the economic development and growth are stably high. According to South East Asia Outlook 2013 that 22% of ASEAN population 600 million, cannot access to electricity [6].



Total Indonesia's fossil energy resources was equivalent to 137000 Million tonnes of oil equivalent (Mtoe) in 2012. Renewable energy was accounted for 155.3 Gwe in 2012 [7]. To reduce CO₂ emission into atmosphere, and mitigate global energy crisis, many trials, and research and developments are carried out for alternative and renewable energy resources such as wind power, solar energy, micro-hydraulic power, geothermal energy and biomass energy. Biomass energy has been estimated that 20 kW power plant could replace 125 t CO₂ per year as compared to electricity generating unit through grid [8].

Pyrolysis is a thermochemical process during which biomass feedstocks are broken down using heat in the absence of oxygen. The pyrolysis process may be represented by a generic reaction such as [9]:



The condensable gas may break down further into noncondensable gases (CO, CO₂, H₂, and CH₄), liquid, and char [9]. Jieheng Guo [10] carried out pyrolysis experiments at the heating rates of 20 K.min⁻¹, 40 K.min⁻¹ and 60 K.min⁻¹, respectively. Kinetics model wood pyrolysis as:

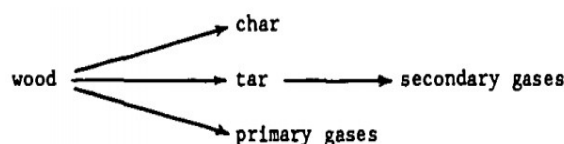


Figure 1. Kinetics Model wood pyrolysis [11]

In the previous experiments [12], the maximum temperature in the pre-vacuum chamber was 600 °C at the chamber bottom and 350 °C at the top of the chamber.

The tar yield from the pilot plant is significantly large, around 40 wt% of feedstock. This tar was produced under 600 °C, which may be primary tar according to the other researcher's experiment [13]. To increase the plant efficiency, the primary tar must be decomposed into secondary one.

Tar is a complex mixture of organics that is produced during thermochemical biomass conversion processes. The chemical formula of tar in the previous numerical analysis [14] was hypothetically defined as C₉H₁₈O₄ for convenience sake. Phuphuakrat Thana, Namioka Tomoaki, Yoshikawa Kunio [15] carried out thermal tar decomposition at temperature of 800 °C. The pyrolysis tar was effectively decomposed, down to approximately 22% of the inlet level at the exit of the reformer. To improve the efficiency of tar reduction, either steam or air was introduced into the reformer, as a reforming agent [15]. Paethanom, et al [16] indicated that at the temperature 800 °C char had the optimum tar removal performance in which tar concentration could be reduced from 36.9 to 4.6 g/m³, which corresponds to 87.5% tar removal, whereas 600 and 1000 °C char possessed the performances of 82.9% and 81.6% tar removal, respectively. The adsorption capacity of char is related to the specific surface area and the fixed carbon content of the char. When temperature reaches about 850 °C, secondary tar gets its peak yield and starts to cracking afterwards; however, primary tar is almost vanished [17]. M. L. Boroson [18] indicates that at temperature 600 °C, primary tar yield decreases from 52.6 wt% of wood to 36.6 wt% of wood and at temperature 700 °C, the decrease is significant, namely from 52.6% to 16.6%. Linear interpolation suggests that primary tar yield decreases by around 50% at temperature 650 °C. P. O. Morf indicates that at 650 °C, primary tar yield decreases from 31 wt% to 23 wt%. [19]. T. A. Milne, R. J. Evans and N. Abatzoglou research that at temperature 650 °C, decrease of around 40 % in primary tar yield was obtained [20].

This research aims to develop simple and practical pyrolysis technology with enhanced plant performance, namely higher gas yields and lower tar, and CO₂ yields from previous research (Homma, et al) [12].

2. Experiment

2.1. Wood Feedstock and Apparatus

In this research, rubber wood is used for pyrolysis feedstock. In North Sumatera region, there are so many rubber plantations [21]. In figure 2, a pyrolysis system constructed for this research is schematically illustrated. All components of the system are connected with stainless steel pipe of $\frac{1}{2}$ inch in diameter, and the combustion gas inside furnace is exhausted into the chimney and flows into the secondary chamber so that the pyrolysis gases from pre-vacuum chamber can be heated up to decompose existing tar. Collecting data in this experiment is done in two ways, namely without charcoal in the secondary chamber, and by inserting charcoal pyrolysis results of prevacuum chamber into the secondary chamber.

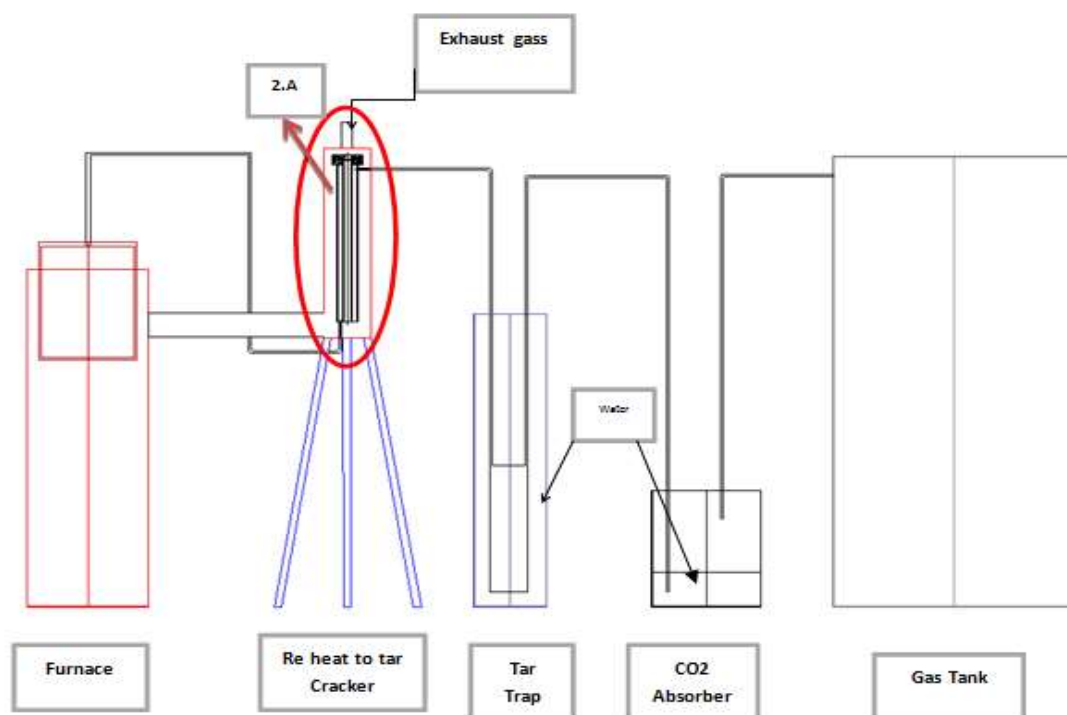


Figure 2. Schematic view of constructed pyrolysis system.

2.2. Experimental Procedures

The procedure is as follows:

- In the pre-vacuum chamber filled with 5 kg rubber wood.
- Water flows in the tar trap at the bottom and flows out from the top, and CO₂ absorber is not filled with water to measure total pyrolysis gases.
- Two K-type of thermocouples are installed properly, namely at pre-vacuum chamber bottom, and at the center of chimney just before the secondary pre-vacuum chamber.
- The equipment is vacuumed.
- Fuels (rubber wood pieces) in the furnace are ignited.
- Temperature, and pressure in the pre-vacuum chamber and the secondary chamber are monitored.
- Pyrolysis gases from the pre-vacuum chamber flow slowly into the secondary pre-vacuum chamber through stainless steel pipes after pyrolysis starts. After reaching 0.1 Mpa, the pressure is kept at 0.1 MPa by opening the valve and releasing pyrolysis gases into the tar trap, gas tank until the pyrolysis process is terminated.

- h. So that the temperature in the secondary chamber can reach 800oC - 1000oC, outside wall of the secondary chamber is wrapped with insulation belt to minimize heat loss.
- i. Record the temperature change every one minute during the pyrolysis process, and the pressure is maintained at 0.1 MPa until the pyrolysis process is complete.
- j. After a pyrolysis experiment has been terminated, the pressure of the gas tank is measured to obtain the gas product volume. Weight of tar trapped in the tar trap is measured.

3. Experimental Result

3.1. Temperature

In the experiment, the exhaust gas temperature was measured just before inlet of the secondary chamber. The result is shown in Figure 3. The exhaust (combustion) gas was moderately heated up as a function of time. In the figure, an arrow mark indicates the moment when the secondary chamber was opened and pyrolysis gases flew out from the chamber. Before the valve opens, the temperature in the primary pre-vacuum chamber is almost same as the date obtained by the previous experiment. However, after 20 minute, the temperature measured by the current experiment is rather lower than that in the previous experiment. The reason for this phenomenon is not clear yet, but it may result from effect of the secondary chamber.

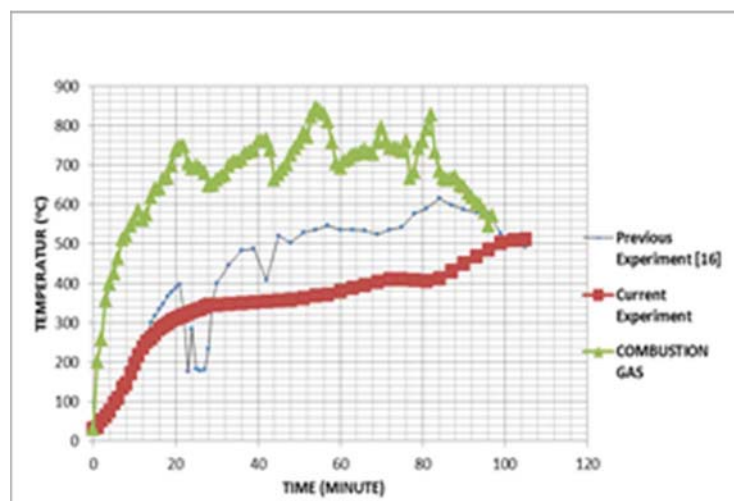


Figure 3. Temperature measure by experiment

The exhaust gas temperature reached 727 C (1000 K) when the valve was opened and then fluctuates around 750 C. For numerical analysis of heat and mass transfer in the secondary chamber, the exhaust gas temperature is approximated by two kinked line. After 20 minutes, the exhaust gas temperature was kept constant at 1000 K.

3.2 Heat and Mass Transfer Analysis Based On Measured Exhaust Gas Temperature

To examine performance of secondary tar cracking in the secondary chamber, heat and mass transfer analysis was carried out by use of Fluent based on measured exhaust gas temperature.

Numerical analysis was carried out for two heating scenarios as follows:

1. Exhaust gas temperature is constant, 1000 K
2. Exhaust gas temperature increases as a bi-linear function of time simulating measured results at the experiment.

In Scenario I, exhaust gas heated up to 1000 K flows into the chimneys inside and outside the secondary chamber, and the result is shown in Figure 4.

From the identification results shown in Figure 8, we present 5 samples from 15 testing images that we conduct

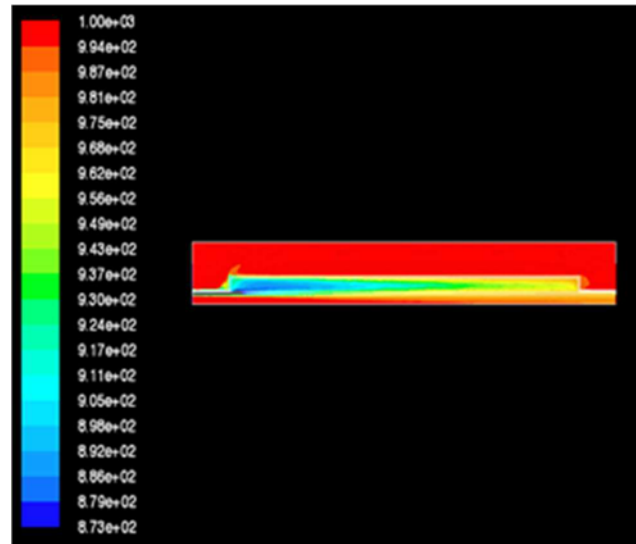


Figure 4. Temperature contours at 40 minutes after heating

In Scenario 2, exhaust gas heated up to the temperature as a function of time as measured in the experiment flows into the secondary chamber. At the same time, pyrolysis gases heated at 500 K flow in the secondary chamber according to the pressure measured in the experiment (Figure 5).

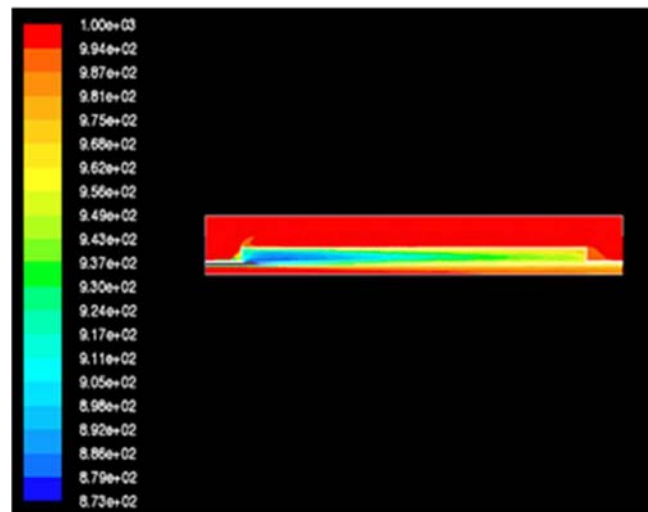


Figure 5. Temperature contours at 40 minutes after heating

As shown in figures 4 and 5, temperature distribution in the secondary chamber is almost the same for both Scenarios. At the upper part of the secondary chamber, pyrolysis gas temperature is above 950 K (677 C). This result can suggest that secondary tar cracking may take place in the secondary chamber.

3.3 Pyrolysis Yields

After the experiment is terminated, pyrolysis yields of tar, char, and gases were measured and shows in Table 1 and 2.

Table 1. Previous pyrolysis yield (mass) for 5 kg rubber wood and pressure 0.1 MPa

PREVIOUS DATA					
	Experiment			Average	%
	1	2	3		
Tar (kg)	2.09	1.73	2.07	1.96	39.29
Char (kg)	1.55	1.25	1.5	1.43	28.67
Gas (kg)	1.36	2.02	1.43	1.60	32.07

Table 2. Current pyrolysis yield (mass) for 5 kg rubber wood and pressure 0.1 MPa

CURRENT DATA					
	Experiment			Average	%
	1	2	3		
Tar (kg)	2.02	1.81	1.653	1.83	36.55
Char (kg)	1.399	1.443	1.764	1.54	30.71
Gas (kg)	1.581	1.747	1.583	1.64	32.74

3.4. Discussion

The experimental results shows that the tar yield is not significantly reduced from the result obtained by the previous experiment in which the secondary chamber was not utilized to promote the secondary tar cracking. To examine performance of the secondary chamber developed by this research, heat and mass transfer analysis was carried out by use of numerical fluid dynamics code Fluent.

The numerical analysis results show that:

1. Axisymmetric heat and mass transfer analysis was carried out for simplicity, although the geometry is not completely axisymmetric, especially, exhaust gas and pyrolysis gas inlets and outlets. However, other geometry and dimensions are the same as those of the secondary chamber used in the experiment.
2. Two scenarios are considered for the numerical analysis.
 - a. The first one is an ideal case. The exhaust gas temperature is kept constant 1000 K
 - b. The second is a case to simulate the experiment, namely, the exhaust gas is gradually heated up to 1000 K at 20 minutes after heating.

Numerical result obtained by Scenario 2 could suggest that the secondary tar cracking may surely take place in the secondary chamber, based on the temperature of more than 650o C and the residence time of around 50 seconds.

4. Conclusion

The pyrolysis technology developed by this research is rather simple and does not needs special technical skill and knowledge. Therefore, the pyrolysis plant can run without less maintenance, and it can be easily installed in rural areas where woods waste is available.

The experimental results showed that the tar yield was not significantly reduced from the previous experimental result. However, in order to enhance efficiency and performance of this pilot plant,

there are many parameters affecting performance of this pilot plant to be clarified. The experimental result and numerical analysis of temperature distribution in the secondary chamber show that secondary tar cracking surely takes place in the secondary chamber, but the primary tar reduction is not apparent. Further experiments are necessary to make sure the secondary tar cracking.

Acknowledgement

The authors would like to express their deepest appreciation to Mr. Kosasih Matseh who supplied rubber wood pieces for feedstock used in this research.

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