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Energy Recovery from Pyrolysis and Gasification of Mangrove

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Abstract

Mangrove is a biomass material that grows in wetland sea waters and is often used to produce charcoal due to its unique characteristics of long and sustained burning and negligible residue. High temperature pyrolysis has been conducted for mangrove biomass in a laboratory scale semi-batch reactor. The effect of reactor temperature on syngas yield and syngas characteristics has been investigated. Reactor temperature was varied from 600 to 900oC in 100oC intervals. The increase in reactor temperature resulted in increased syngas yield, hydrogen yield and energy yield. Evolutionary behavior of the syngas characteristics has also been investigated. The increase in reactor temperature increased the peak value of syngas flow rate, hydrogen flow rate and output power. The increase in reactor temperature decreased the time duration of pyrolysis. Cumulative yield of syngas, hydrogen and energy was calculated based on the time dependent relationship. Higher reactor temperatures shortened the time duration required for 99% release of syngas, hydrogen and energy. For example, time duration required for 99% yield of hydrogen was approximately 73 minutes at 600oC and only about 26 minutes at 900oC. Required time duration for 99% yield of energy was ~62 minutes at 600oC and ~15 minutes at 900oC. The gasification of the same material at 900oC has been carried out to determine the role of gasifying agent on the fate of material and resulting syngas properties. The results showed gasification yielded more syngas, hydrogen and energy than that obtained from pyrolysis.

Keywords: pyrolysis, gasification, biomass, syngas, hydrogen yield

1. Introduction

Greater use of renewable energy sources is of pinnacle importance especially with the limited known reserves of fossil fuels. It is expected that future energy portfolio will have increased utilization of different energy sources, including biomass, municipal solid wastes, industrial wastes, agricultural wastes and other low grade fuels.

Development of sustainable renewable energy technologies for their use in current and new power plants is of greater importance now than ever before due to several reasons. Some of these reasons include energy security and availability, independency from foreign oils and reduction of greenhouse gas emissions to provide cleaner environment for better health and plant and animal life. These reasons dictate the development of alternative and sustainable energy technologies. Gasification and/or pyrolysis provide part of the solution towards dependable renewable energy source.

The mangrove forest or intertidal forest is defined as a group of plants grown along the hide and low tide seashore areas found mostly at seashore, estuary, lake and island. Mangrove has been utilized for a variety of purposes such as charcoal, timber, firewood, and wood chips production. Tens of millions of people around the tropic and sub tropic areas depend on mangrove forests as a source of fuel wood, charcoal, timber, and other non timber products. Although charcoal has traditionally been used for daily cooking by coastal villagers and rural household, in recent years it has been exploited as a commercial product particularly in Thailand, where now mangrove charcoal are exported to Europe and Asia. High quality charcoal is characterized by high percentage of fixed carbon, low ash content, low moisture content with high specific gravity. Mangrove charcoal is highly preferred mainly because of its special qualities that ordinary charcoal often does not possess. In particular the absence of fire bursts during use, steady burning over a long period and the handling convenience [1, 2].

Based on the most recent estimation the areas covers by mangrove forests gave a total of 18.1 million ha worldwide. South and Southeast Asia having 41.5 %, the Americas 27.1 %, West Africa 15.5 %, East Africa and Middle East 55 % and Australasia 10.4 %. Mangrove charcoal production is found in many Southeast Asian countries such as Thailand, Peninsular Malaysia, Vietnam, and on the east coast of Sumatra of Indonesia. The mangroves in Southeast Asia region cover an estimated area of about 3.95 million ha [3].

The most suitable species for charcoal making are those that have high density values. This specie belongs to the Rhizophoraceae tropical family. Its physical characteristics are as following: density of 0.86 kg/m3, moisture content of 13.89% and specific gravity of 0.92 [4]. Consequently, the Rhizophoraceae type of

Fig. 1: Mangrove sample

Fig. 2: Char yield from Mangrove pyrolysis at different reactor temperatures

Mangrove was used in the experiments. Because of the high quality charcoal obtained from mangrove, it is an excellent candidate for energy recovery by pyrolysis or gasification. Mangrove pyrolysis was conducted at reactor temperature of 600, 700, 800 and 900oC. Gasification experiment at 900oC was conducted for comparison.

Figure 1 shows a sample of the Mangrove biomass material sample as received. Figure 2 shows the char yield after pyrolysis of this material at four different temperatures of 600, 700, 800 and 900^{o}Cs. One can see that the increase in reactor temperature resulted in reduced mass of the material. The reason for higher char yield at lower temperatures is possible trapping of the volatile matter in form of coke inside the material.

2. Experimental

Figure 3 shows a photograph of the laboratory scale experimental facility used for pyrolysis and gasification experiments. For pyrolysis experiments, a pure nitrogen flow was used as the inert medium. Nitrogen was heated in the pre-conditioning reactor, which is used to pre-heat the inert gas for pyrolysis experiments or heat steam incase of gasification experiments.

For gasification experiments pure steam is generated by stoichiometric combustion of hydrogen and oxygen. Steam generated is then introduced into the gasifying agent conditioner section so that the temperature of the gasifying agent is at the same temperature as that of the main reactor in which the gasification occurs. The sample material undergoes gasification in the main reactor. Steam is then introduced to the main reaction chamber.

The syngas flowing out from the main reaction chamber is sub-divided into two branches; one passes to the sampling line while the other is allowed to pass through the exhaust system. The bypass line has a non-return valve and a flow meter to assure a unidirectional flow out from the reactor. The syngas sample is then introduced to a condenser followed by a low pressure filter and a moister absorber (anhydrous calcium sulfate). Syngas flow is then introduced to a three way valve that allows one to fill the sampling bottle or introduce the syngas directly to the micro GC for detailed analysis of the syngas produced. Sampling bottles are used only when short sampling intervals are needed (0.5 to 1 min). Direct sampling and analysis are carried out by the GC when longer sampling time intervals are desired.

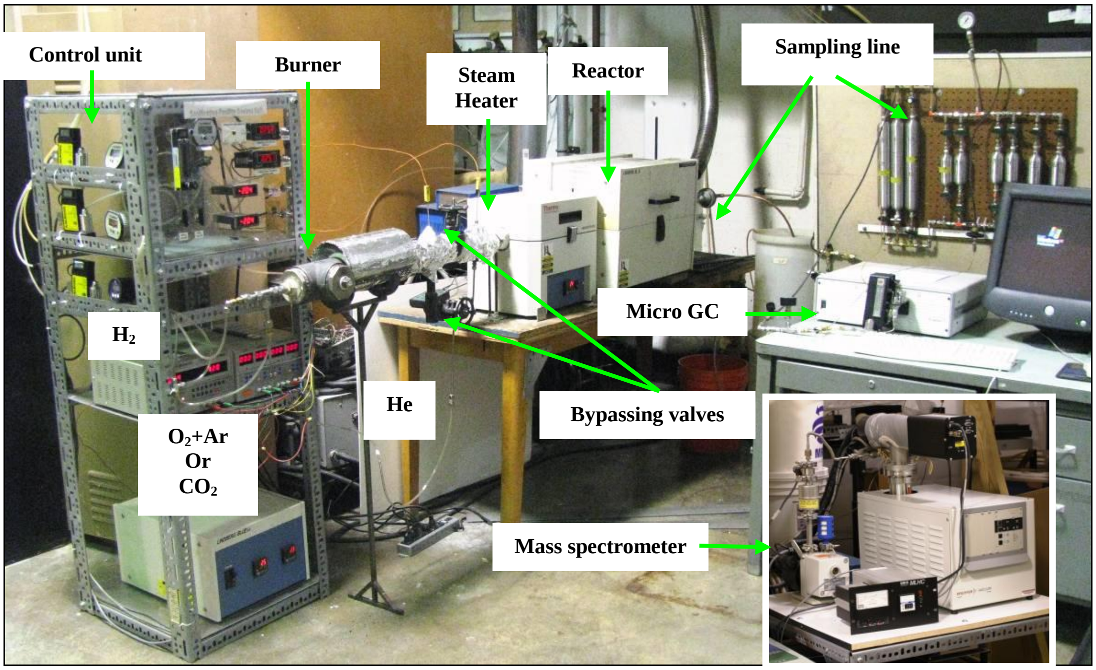

Fig. 3: A photograph of the experimental facility

In case of gasification, a constant flow rate of nitrogen is introduced with the oxygen flow. The nitrogen is detected by the GC and is used to determine the flow rate of different syngas species by comparing the detected species mole fraction with the known nitrogen mole fraction. This technique has been used in previous investigations for determining syngas evolutionary behavior and properties and was proven successful [5-13]. In case of pyrolysis experiments, nitrogen flow provides the inert medium and the used in syngas species flow rate calculations as well.

2.1. Experimental conditions

Reactor temperature for pyrolysis: 600, 700, 800 and 900°C

Inert/trace gas: 3 g/min of Nitrogen

Reactor temperature for gasification: 900°C,

Steam flow rate: 7.72 g/min

3. Results and discussion

Presented in this section are the evolution of syngas, hydrogen and output power for the investigated temperatures. The overall yield of syngas, hydrogen and energy was calculated based on the respective property-time relationship. Results of syngas, hydrogen and energy yield from gasification experiment at 900°C are presented for comparison to that obtained from pyrolysis.

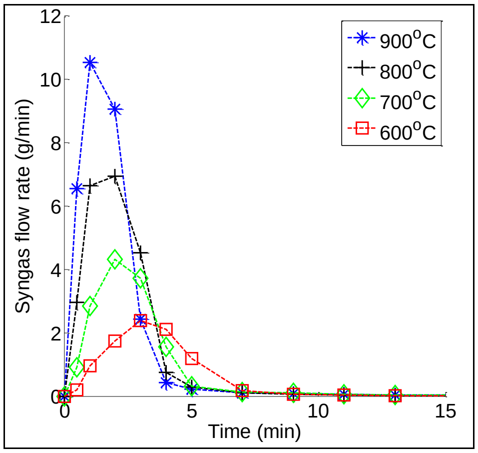

Fig. 4: Syngas flow rate (Mangrove pyrolysis)

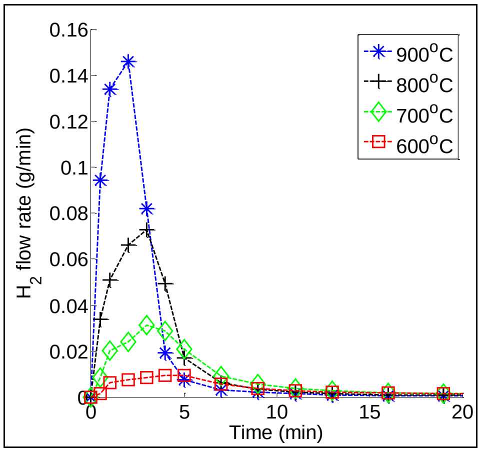

Fig. 5: Hydrogen flow rate (Mangrove pyrolysis)

Figure 4 shows the evolution of syngas from Mangrove pyrolysis at reactor temperatures 600, 700, 800 and 900°C. The in crease in reactor temperature resulted in the increase in syngas flow rate. The increase in reactor temperature resulted in the shift of peak flow rate value towards shorter time. The peak syngas flow rate occurred at the 3rd, 2nd, 2nd, and 1st minute for reactor temperatures 600, 700 and 800 and 900°C respectively.

Figure 5 shows the evolution of hydrogen flow rate from Mangrove pyrolysis at reactor temperatures 600, 700, 800 and 900°C. Following the same trend as the syngas flow rate, hydrogen flow rate increased by the increase in reactor temperature. Peak values of hydrogen flow rate were shifted towards shorter time period as result of the increase in reactor temperature. The peak hydrogen flow rate occurred at the 4th, 3rd, 3rd, and 2nd minute for reactor temperatures 600, 700 and 800 and 900°C respectively.

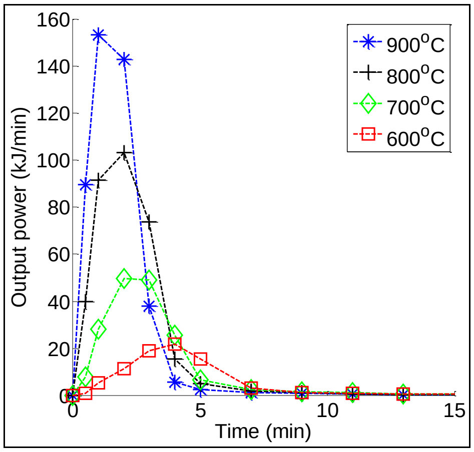

Fig. 6: Output power (Mangrove pyrolysis)

Figure 6 shows the evolution of output power from the Mangrove pyrolysis. Following the same trend as syngas flow rate and hydrogen flow rate, the output power increased by the increase in reactor temperature.

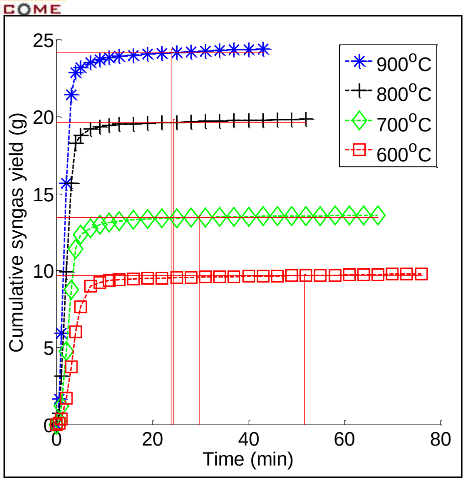

Fig. 7: Cumulative syngas yield (Mangrove pyrolysis)

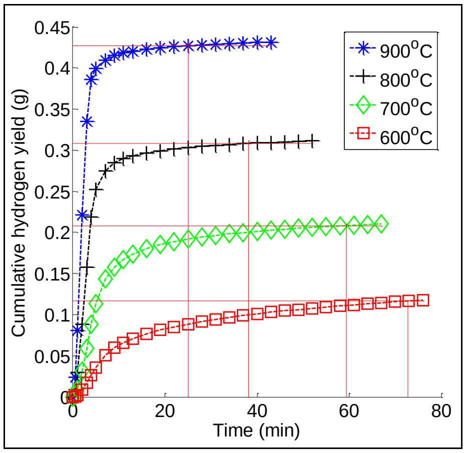

Fig. 8: Cumulative hydrogen yield (Mangrove pyrolysis)

Figures 7, 8 and 9 show the cumulative yield of syngas, hydrogen and energy. The horizontal lines in the figures represent the 99% property yield. The vertical lines represent the time, ($t_{99\%}$) at which 99% of syngas, hydrogen or energy has evolved. The fast evolution of syngas in the first five minutes resulted in a steep slop of cumulative syngas yield, hydrogen yield and energy yield. One can see that higher the reactor temperature, steeper is the slop of syngas, hydrogen and energy yield. The increase in reactor temperature resulted in the decrease of time duration at which syngas, hydrogen and energy reaches the 99% conversion value.

The cumulative plots are useful in determining required residence time for a sample to reach a certain conversion value. 99% is an arbitrary number; it can be 95% or even 90% depending on the designer goals and limitations. The reactor temperature tremendously affected the $t_{99\%}$ value for hydrogen and energy yield; the increase in reactor temperature from 600°C to 900°C decreased the $t_{99\%}$ for hydrogen yield from ~73 minutes to ~26 minutes and decreased the $t_{99\%}$ for energy yield from ~62 minutes to ~15 minutes.

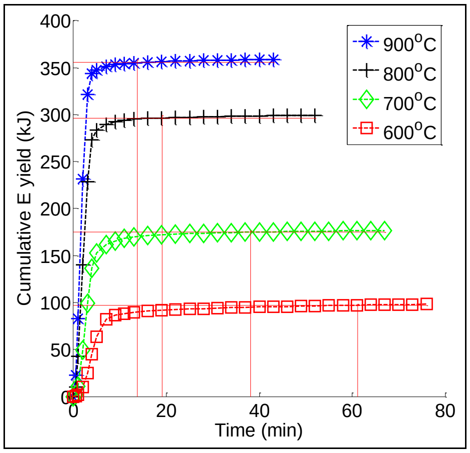

Fig. 9: Cumulative energy yield (Mangrove pyrolysis)

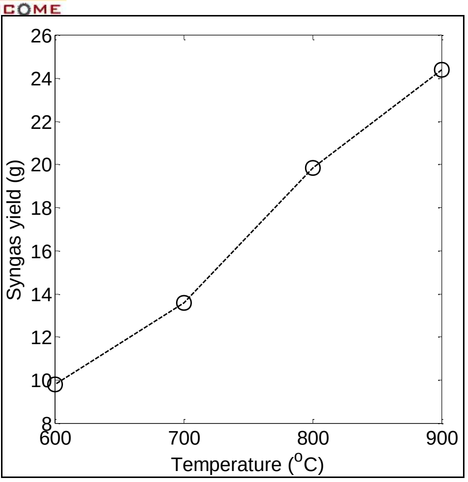

Fig. 10: Effect of temperature on syngas yield

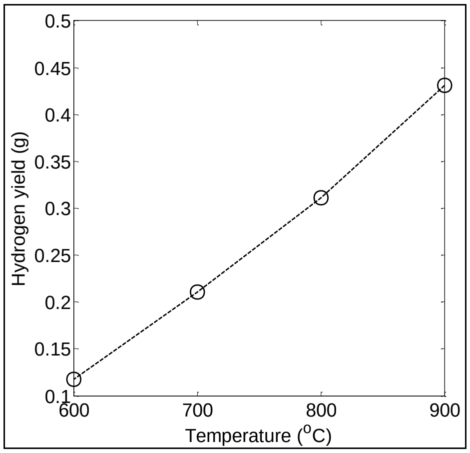

Fig. 11: Effect of temperature on hydrogen yield

Figure 10 show the effect of temperature on overall syngas yield. The increase in temperature resulted in an increase in syngas yield. The syngas yield increased from 10 grams to 24 grams when the reactor temperature increased from 600^{o}C to 900^{o}C. This increase in syngas yield indicates an equivalent decrease in tar yield. Mangrove pyrolysis yielded more syngas than that obtained from food waste pyrolysis and paper pyrolysis at same experimental conditions. Syngas yield from food wastes pyrolysis and paper pyrolysis was 13.5 and 15.1 grams respectively []. Figure 11 show the hydrogen yield. Hydrogen yield followed a quasi-linear increase as a function in reactor temperature. Hydrogen yield was 0.43 grams at 900^{o}C, which is higher than that obtained from food waste pyrolysis and paper pyrolysis at same experimental conditions. The hydrogen yield from food waste pyrolysis and paper pyrolysis was 0.2 and 0.24 grams respectively []. Higher syngas and hydrogen yield from mangrove is mainly attributed to the high volatile content in the sample. Figure 12 shows the effect of reactor temperature on energy yield. The energy yield is following a very similar trend as the syngas yield. The energy yield was increased more than three times by the increase in temperature from 600 to 900^{o}C. On the other hand, the $t_{99\%}$ value decreased from ~62 minutes to ~15 minutes.

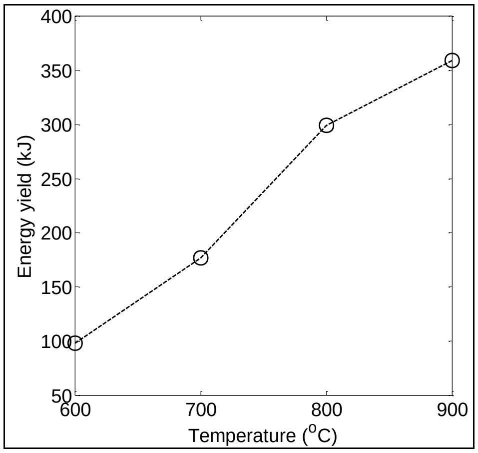

Fig. 12: Effect of temperature on energy yield

Figures 13, 14 and 15 show the cumulative yield of syngas, hydrogen and energy form pyrolysis compared to that from gasification. In the first few minutes, 0 to 5 minutes, the cumulative syngas yield, hydrogen yield and energy yield from pyrolysis and gasification coincides on each other. This indicates that syngas evolution during the initial stage is mainly attributed to pyrolysis. After the fifth minute the cumulative yield from gasification is showing a quasi-linear increase in time for the three investigated properties; syngas, hydrogen and energy. Gasification yielded more syngas, hydrogen and energy than that from pyrolysis. Syngas and energy yield from gasification was almost double that was obtained from pyrolysis at 900°C. Hydrogen yield from gasification was more than five times that was obtained from pyrolysis at 900°C. In spite the higher yield from gasification, 99% of syngas and hydrogen has evolved in about the same time duration as that from pyrolysis.

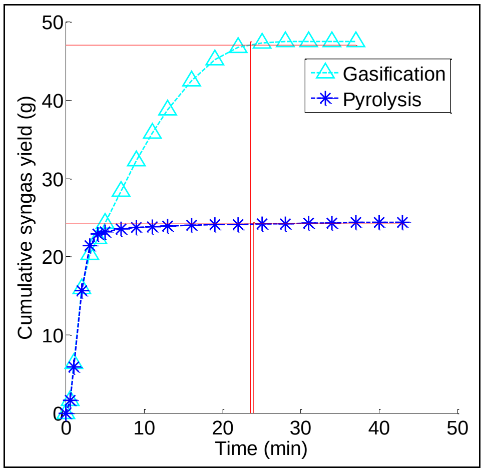

Fig. 13: Cumulative syngas yield from pyrolysis and gasification at 900°C

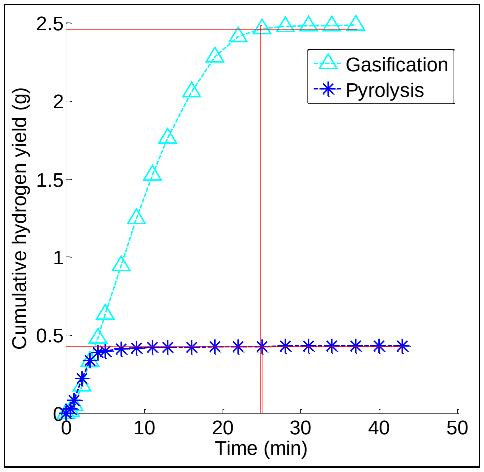

Fig. 14: Cumulative hydrogen yield from pyrolysis and gasification at 900°C

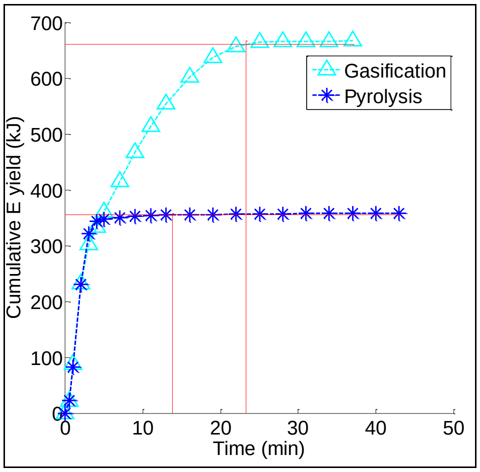

Fig. 15: Cumulative energy yield from pyrolysis and gasification at 900°C

Figures 16, 17 and 18 show the evolution of syngas flow rate, hydrogen flow rate and output power from gasification compared to that from pyrolysis. Syngas flow rate, hydrogen flow rate and output power from gasification and pyrolysis coincides on each other in the first few minutes. The area confined between the gasification curves and pyrolysis curves represents the added syngas, hydrogen and energy due to char gasification and tar reforming. It is important to note that steam gasification resulted in higher hydrogen flow rate and yield than that from pyrolysis.

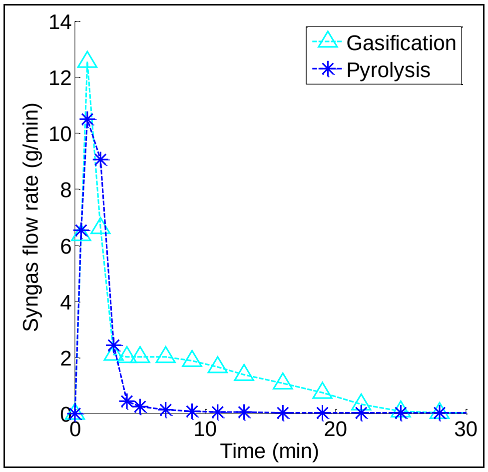

Fig. 16: Syngas flow rate from pyrolysis and gasification at 900^{o}C

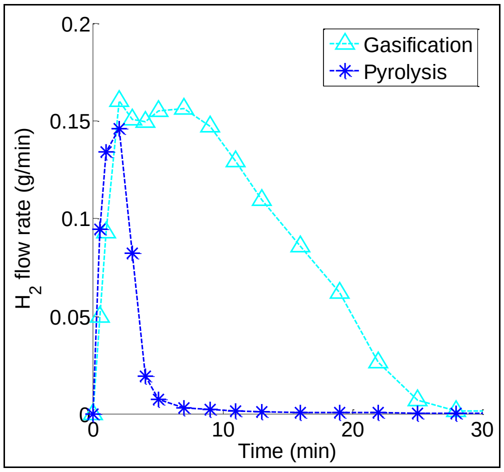

Fig. 17: Hydrogen flow rate from pyrolysis and gasification at 900^{o}C

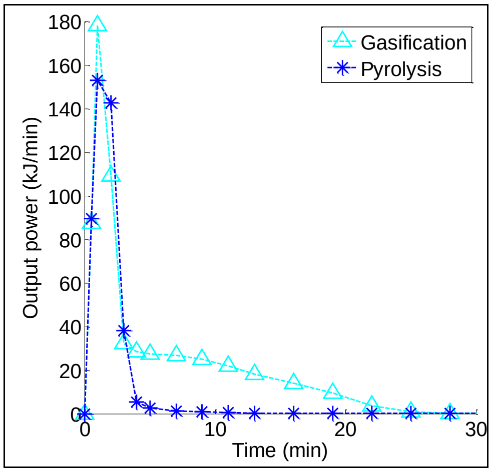

Fig. 18: Output power from pyrolysis and gasification at 900^{o}C

Conclusions

Mangrove pyrolysis experiments were conducted in a semi-batch reactor. Effect of reactor temperature on syngas yield and characteristics was investigated. Reactor temperature varied from 600 to 900oC in 100oC intervals. The increase in reactor temperature resulted in an increase in syngas yield, hydrogen yield and energy yield. Mangrove pyrolysis yielded more syngas than that obtained from food waste pyrolysis and paper pyrolysis at same experimental conditions. Syngas yield from food wastes pyrolysis and paper pyrolysis was 13.5 and 15.1 grams respectively. Hydrogen yield was 0.43 grams at 900^{o}C, which is higher than that obtained from food waste pyrolysis and paper pyrolysis at same experimental conditions. The hydrogen yield from food waste pyrolysis and paper pyrolysis was 0.2 and 0.24 grams respectively. Higher syngas and hydrogen yield from mangrove is mainly attributed to the high volatile content in the sample.

Higher reactor temperatures resulted in shorted time duration required for 99% release of syngas, hydrogen and energy. For example, required time duration for 99% yield of hydrogen was ~73 minutes at 600°C and ~26 minutes at 900°C. Required time duration for 99% yield of energy was ~62 minutes and ~15 minutes at 900°C. Gasification experiment was conducted at 900°C for comparison. Gasification yielded more syngas, hydrogen and energy than pyrolysis. Syngas and energy yield from gasification was almost double that was obtained from pyrolysis at 900°C. Hydrogen yield from gasification was more than five times that was obtained from pyrolysis at 900°C.

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