Optimizing Biomass Pyrolysis Through Joule Heating with Focus on Reaction Parameters and Product Quality

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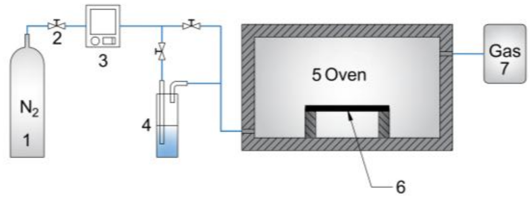
Biomass is a promising renewable energy source that can replace fossil fuels due to its wide availability, high yield, and carbon neutrality (Ali et al., 2024). Pyrolysis, a thermochemical process, is commonly used to convert biomass into bio-oil, syngas, and biochar (Arshad, 2024). However, traditional pyrolysis methods are limited by slow heating rates and uneven temperature distribution, which reduce reaction efficiency and product quality (Wu et al., 2022). Joule heating provides rapid (millisecond level) and uniform heating, making pyrolysis reactions more efficient and focused (Sun et al., 2022). This technology also allows precise control when combined with pulse modulation and pressure adjustment (Selvam et al., 2024). Despite these advantages, the reaction mechanisms and key factors influencing joule heating pyrolysis remain unclear. This study explores the effects of temperature, pressure, pulse cycles, and additives such as water vapor and activated carbon on biomass pyrolysis using joule heating.

As shown in Fig. 1, biomass was wrapped in carbon paper and placed inside the joule heating reactor. The carrier gas flowed into the reactor from the bottom, and the gases produced during the reaction were collected in a gas bag for analysis using gas chromatography (GC). As shown in Fig.2, the reaction temperatures were set to 600 ℃ and 800 ℃, with reaction pressure either at atmospheric pressure or under a vacuum of 0.08 MPa. The total heating time was set to 5 s or 10 s, with heating pulses of 1, 2, or 4 cycles. For the experiments at 800 ℃, additional tests were performed by introducing water through a wash cylinder. Biomass samples mixed with 10% activated carbon were tested under conditions with and without water. Residual carbon samples from reactions under specific conditions were collected for further analysis. Fig. 2 also highlights the marked samples (e.g., 1#, 2#, 3#, etc.) that were selected for characterization using SEM, TEM, and temperature-programmed oxidation (TPO).

Results showed that, under the condition of 10 s heating time, the biomass conversion rates at both 600 ℃ and 800℃ were similar. However, at 600 ℃, gas yield decreased with multiple pulses because intermittent cooling impeded the pyrolysis process. In contrast, at 800 ℃, gas yield increased with additional pulses. This was likely due to repeated heating, which promoted secondary reactions. Under 5 s heating time, the biomass conversion rate at 600 ℃ was extremly low, indicating that the main pyrolysis stage had not started. At 800 ℃, the biomass conversion rate was similar to that at 10 s, but the gas yield was significantly lower. This suggests that the secondary reactions did not occur during the first 5 s. Across all conditions, atmospheric pressure consistently produced higher gas yields than vacuum. This demonstrates the importance of pressure in retaining volatile compounds for secondary reactions. Further experiments introduced water vapor through a wash cylinder and tested the effects of adding 10% activated carbon. These experiments explored the impact of steam reforming and the formation of carbon nanotubes (CNTs). Under 800 ℃ conditions, water injection significantly boosted hydrogen production, but only when activated carbon was present. This suggests a catalytic role for activated carbon. Pure biomass showed minimal response to added steam, indicating that biomass alone lacks sufficient catalytic activity. SEM and TEM images confirmed the presence of CNTs in samples containing activated carbon. However, water injection partially suppressed their formation. TPO analyses showed that samples rich in CNTs exhibited enhanced thermal stability. These findings highlight that precise control of temperature, pressure, and additives can effectively tailor both gaseous products and solid carbon structures during joule heating pyrolysis of biomass.

To sum up, this study investigated joule heating biomass pyrolysis under different reaction conditions, including temperature (600 ℃, 800 ℃), pressure (vacuum, atmosphere), heating time (5 s, 10 s), number of pules(1, 2, and 4), as well as additives (water vapor and activated carbon). The results showed that temperature and heating time significantly influenced biomass conversion. Temperature, heating time, and the number of pules had a major impact on gas yield and composition. The addition of activated carbon and water vapor affected the formation of carbon materials. SEM, TEM, and TPO analyses confirmed the formation of CNTs, which enhanced the thermal stability of the residual carbon. Overall, this study demonstrates a new approach to producing clean fuel and functional carbon materials from biomass.



1. N_2; 2. valve; 3. mass flow meter; 4. wash cylinder; 5. oven; 6. biomass packed by carbon paper; 7 gas bag

Fig. 1. Experimental Design of Joule Heating Pyrolysis

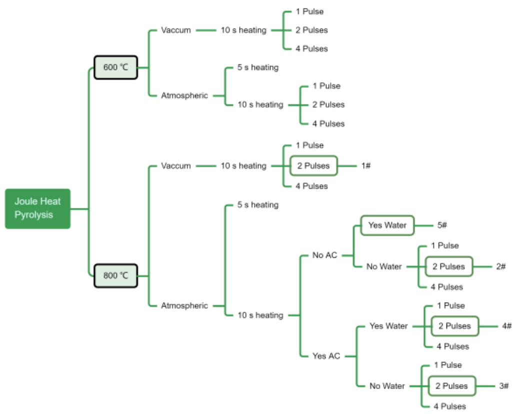


Fig. 2. Experimental Technology Roadmap

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