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Thermochemical Conversion of Palm Woody Biomass: Ways to Reduce the Tar

Haider Khan, and Isam Janajreh*

Department of Mechanical Engineering, Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates

*Corresponding author. Tel: +971-2-312-3286; Email: Isam.Janajreh@ku.ac.ae

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1. Introduction

Biomass gasification is a promising pathway for sustainable energy production, particularly regions where palm woody biomass abundant, a byproduct of the date industry, (Adeyemi et al., 2017). However, tar formation remains a significant challenge in biomass gasification, leading to operational inefficiencies, including clogging, catalyst deactivation, and reduced energy conversion efficiency (Abu El-Rub et al., 2004). Conventional catalytic tar cracking, though effective, is limited by high costs and susceptibility to heavy metal poisoning (Chen et al., 2000). This numerical study investigates an alternative approach to optimize thermal tar cracking, focusing on reactor design and operational parameters to enhance tar decomposition. A thermogravimetric analysis (TGA) of palm biomass gasification is conducted to infer the tar formation and their kinetics. The decomposition and their rates will be integrated into a 3D CFD gasification model subjected to varying conditions (wall temperature, pressure, and residence time) aiming at maximizing syngas production and eliminating undesirable tars at the gasifier exit.

2. Methodology

2.1 Biomass Characterization

Palm woody biomass, consisting of trunk and leaves, was collected and milled and sieved into a fine mesh size < 0.5 mm. The samples were dried at 105°C to remove moisture before undergoing proximate anaylysis via thermogravimetric analyser (TGA) and ultimate analysis to determine their composition. The TGA experiments were conducted using a Thermo-Scientific STA Q600 analyzer, operating under a nitrogen atmosphere at various heating rates from room temperature to 900°C. The elemental composition and calorific value were measured using a Thermo-Scientific Flash CHNS-O analyzer and a Parr 6100 bomb calorimeter, respectively.

2.2 Tar Formation and Devolatilization Analysis

To evaluate tar evolution, the biomass samples were subjected to devolatilization studies at temperatures ranging from 400–800°C. The volatile components, including hydrocarbons, CO, CO_2, and tar, were quantified based on the empirical decomposition formula derived from TGA data. The dominant tar species at different temperature ranges were identified using gas chromatography-mass spectrometry (GC-MS), allowing for kinetic modelling of tar decomposition reactions.

2.3 Modeling of Biomass Gasification

A 200 tons/day Mitsubishi gasifier is modelled as 3D computational fluid dynamics (CFD) model to simulate biomass gasification and tar reduction under varying conditions. The model incorporated reaction kinetics derived from TGA experiments and considered wall temperature, pressure, residence time, and moderating agents as key parameters. The gasification process was simulated using ANSYS Fluent, employing the finite-rate/Eddy dissipation model to capture the complex tar cracking reactions. A structured mesh with approximately 1.5 million elements was generated to ensure high computational accuracy.

2.4 Tar Reduction through Thermal Cracking

The kinetics of tar decomposition was studied using TGA-based reaction rate analysis, with the Arrhenius parameters (A and E) for major tar components extracted and applied in the CFD model. The effect of wall temperature (900–1300°C), pressure (1–5 bar), and residence time (0.5–2s) on tar conversion efficiency was analyzed. The model was optimized for maximum syngas yield with minimal tar formation.

This methodology integrates experimental TGA analysis, kinetic modeling, and CFD simulations to develop an optimized thermal conversion strategy for palm biomass gasification, addressing tar formation and mitigation challenges.

3. Result and Discussion

3.1 Material Characterization

The STA plots depicted in Fig. 1 and Table 1 for the palm woody biomass offers data regarding the proximate and ultimate analysis components, including moisture, volatile matter, and fixed carbon content. Palm woody biomass displays relatively high moisture (8.95%) and volatile matter (68.89%) but lower fixed carbon content (21.88%). It is pertinent to consider the notable disparity in HHV between the palm woody biomass compared to the coal (18.75 vs. 30.46 MJ/kg).

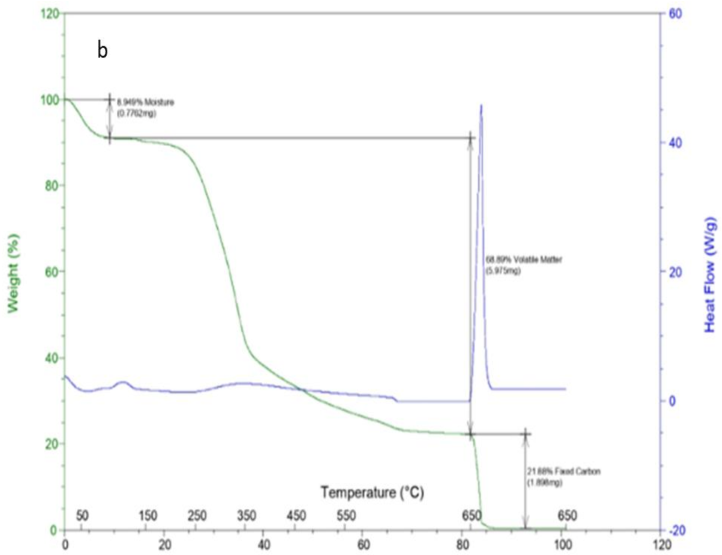

Fig. 1. STA plot of the Palm Woody Biomass

Table 1. Proximate, ultimate, and calorific analyses values of Palm woody biomass

Species	Palm woody biomass $CH_{1.5203}N_{0.0068}S_{0.0003}O_{0.6621}$
Proximate analysis	**Mean**
Moisture (Wt%)	8.95 ± 0.01
Volatile (Wt%)	68.89 ± 0.01
Fixed Carbon (Wt%)	21.88 ± 0.01
Ash (Wt%)	0.18 ± 0.01
Ultimate analysis	**Mean**
C (Wt%)	49.41 ± 0.71
O (Wt%)	43.62 ± 0.23
H (Wt%)	6.26 ± 0.06
N (Wt%)	0.39 ± 0.02
S (Wt%)	0.04 ± 0.01
HHV (MJ/kg)	18.75 ± 0.20

The feasibility of tar reduction in palm woody biomass gasification is significantly influenced by its proximate and ultimate composition. The high volatile matter content (68.89%) indicates a substantial tar formation potential, contributing to tar accumulation within the gasifier. However, the moderate fixed carbon content (21.88%) suggests that sufficient char is available, facilitating secondary tar cracking reactions and enhancing overall gasification efficiency. The high oxygen content (43.62%) supports partial oxidation and steam reforming, promoting tar decomposition and syngas enhancement. Favorable C/H and O/C ratios further enable efficient CO and H_2 conversion. Additionally, the higher heating value (18.2 MJ/kg) confirms that palm biomass possesses adequate energy content to sustain gasification processes with minimal external energy input requirements. Therefore, thermal tar reduction in palm woody biomass gasification is feasible, provided that optimal reactor conditions are maintained to ensure effective tar decomposition and enhanced syngas production.

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