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Tar Removal of Palm Kernel Shell Syngas using Wet Scrubber

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Abstract

In the current situation, biomass gasification has become a major interest in producing clean energy and green chemicals. By gasification, the biomass can be converted to synthetic gas (syngas) for many purposes. However, syngas with high tar content can cause pipeline fouling and disturb the operation of downstream equipment. To reduce tar content, a two-series wet scrubber was installed for syngas cleaning produced by palm kernel shell gasification. Firstly, the gasification is operated at a temperature range of 500 – 600°C and 700 – 800°C to determine the conditions where the lowest tar syngas is produced. After that, the wet scrubber is installed with a variety of solvents including isopropyl alcohol, water, used cooking oil, and used lubricating oil. The results show that the lowest tar syngas was produced at a temperature of 800°C with a tar yield of 0.165 g/kg biomass. Meanwhile, in the same condition, isopropyl alcohol delivers the most substantial impact on tar removal efficiency, whereas used lubricating oil results in less impact. The use of isopropyl alcohol resulted in 99.25% tar removal effectiveness while lubricating oil yielded just 50.32%.

Keywords: tar removal, palm kernel shell gasification, wet scrubbers, gasification temperature, low-tar syngas

1. Introduction

In recent years, the world has witnessed growing concern about the environmental impact of conventional energy sources, such as coal, oil, and natural gas. As a result, there has been a remarkable shift towards renewable energy derived from naturally replenishing sources. One of the critical solutions to combating climate change and promoting sustainability is the establishment of renewable energy power plants. The construction and operation of renewable energy power plants bring numerous benefits to society. First and foremost, they help mitigate the adverse effects of climate change by reducing carbon dioxide and other greenhouse gas emissions. This shift towards renewable energy sources also decreases our dependence on fossil fuels, promoting energy security and independence. Moreover, renewable energy power plants create job opportunities, stimulate economic growth, and foster technological advancements in the clean energy sector.

Palm kernel shell (PKS) gasification is an innovative and environmentally friendly method of generating energy from agricultural waste (Pranolo et al., 2022). In addition to the abundant amount, PKS has a high calorific value. By gasification technology, PKS can be converted into combustible gas, commonly known as syngas. The syngas primarily consists of carbon monoxide (CO), hydrogen (H_2), and methane (CH_4), which can be used as fuel for various applications. It can be burned directly in a gas turbine or an internal combustion engine to generate electricity. Alternatively, the syngas can be further processed to produce biofuels, chemicals, or heat for industrial processes, making it a versatile energy resource.

However, the syngas still contains a complex mixture of organic compounds known as tar. The mixture substances range from organic components to light components such as benzene and phenol to polynuclear aromatic hydrocarbons (PAHs) (Dafiqurrohman et al., 2020). The presence of tar in the syngas can have detrimental effects on downstream processes and utilization, such as equipment fouling and catalyst deactivation. When

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introduced into an internal combustion engine, tar can cause various issues. Tar particles can clog the fuel filters and injectors, obstructing fuel flow to the engine cylinders (Unyaphan et al., 2017). This can lead to fuel starvation, misfiring, and poor combustion. The clogging of injectors can also cause an uneven fuel distribution among the cylinders, resulting in engine imbalance and performance reduction.

Tar production occurs predominantly during the pyrolysis stage of biomass gasification. When lignocellulosic biomass is not fully converted, tar production is significant, especially at low temperatures. Tar is a heterogeneous collection of molecules whose makeup is largely determined by the biomass used, the gasifier's architecture, and the process parameters. Tar production can be reduced in several ways: (i) by improving gasifier design and cleaning system configuration; (ii) by modifying operational parameters including temperature, pressure, gasifying agent, and steam-to-biomass ratio; and (iii) by using catalysts (Cortazar et al., 2023). Pranolo and Research team (Pranolo et al., 2019) conducted an experiment to reduce tar content in syngas by modifying the process flow in the gasifier. Pranolo reuses the syngas produced by recycling the syngas resulting from cocoa pod husk gasification back into the reactor. At a syngas volume ratio per gasifying agent (air) of 9% and a feedstock size of 1 inch, the tar content in the syngas was successfully reduced to 97%. However, the heating value of the syngas produced decreases due to the increase in nitrogen content carried by the recycled syngas.

Catalytic and tar thermal is not economically viable since it necessitates a high amount of thermal energy for biomass and tar conversion (Anis & Zainal, 2011). Optimizing the syngas cleaning methods is a promising strategy for lowering tar content which is less expensive and delivers significant tar reduction. One of the methods is the syngas cooling system. The system typically consists of a series of heat exchangers and condensers that use a cooling medium, such as water or air, to lower the temperature of the syngas. As the syngas is cooled, tar compounds undergo a phase change from a gaseous state to a liquid state. These condensed tars are then separated from the syngas stream using various methods, such as gravity settling or cyclone separators. Previous study reported by (Pranolo et al., 2022) shows that one pass shell and tube heat exchanger can reduce tar content from palm kernel shell's syngas up to value of 8.67 g/Nm^3. In another study, (Thapa et al., 2017) used the same type of heat exchanger resulting in a tar content of 27 g/Nm^3 in switchgrass's syngas. By changing the heat exchanger design from one pass to two pass shell and tube heat exchanger, (Thapa et al., 2019) reported the tar content from switchgrass's syngas can reduce up to value 12.7 g/Nm^3. However, these values remain distant from allowable limit of tar content for compressor and internal combustion engine applications, which are 0.5 g/Nm^3 and 0.1 g/Nm^3, respectively (Baratieri et al., 2009; Asadullah, 2014; Hasler & Nussbaumer, 1999; Singh et al., 2013).

Overall, there are two basic approaches to tar removal: gasifier-based tar removal (primary) and tar removal in the cleaning equipment (secondary). The primary method often entails optimizing the gasifier's configuration, employing in situ catalysts, and effectively regulating operating parameters such as temperature, equivalency ratio, and gasification agent. The secondary method does not interfere with the gasifier operation. It can be categorized as physical (cyclones, condenser, scrubber, etc.) or chemical treatments (thermal and catalytic processes). While primary methods for tar elimination may lower the cost of the operation, they may not be sufficiently efficient in completely removing all tar. Merging two methods is an effective approach.

In this study, a combination of the above methods was carried out by investigating the effect of gasification temperature and installing the wet scrubber after the reactor. The gasification operating temperature is operated in two different temperature ranges, at 500 – 600^{o}C and 700 – 800^{o}C. Meanwhile, the wet scrubber is installed in series with dimensions of 110 mm x 110 mm x 110 mm, and it contains various solvents for tar reduction such as isopropyl alcohol (IPA), water, used culinary oil (UCO), and used lubricant oil (ULO). The study investigates the optimum operating temperature of PKS gasification and the most suitable wet scrubber solvent for the production of low-tar syngas from PKS.

2. Methodology

2.1. Materials

PKS was used as a feedstock for gasification. It originated from one of Indonesia's West Kalimantan palm oil refinery industries and has a uniform size of 2 - 3 cm, so it does not require special pre-treatment, such as size reduction.

Figure 1. PKS size distribution

Prior to its application, the PKS was characterized. As shown in Table 1, the proximate, ultimate, and heating value characterization was carried out by an accredited third party, namely SUCOFINDO.

Table 1. Proximate and ultimate analysis of PKS

Proximate analysis (wt%. dry basis)	
Volatile matter	70.5
Fixed Carbon	18.3
Ash content	1.7
Moisture content	9.5
Ultimate analysis (wt%. dry basis)	
C	47.6
H	6.37
O	43.9
N	0.31
S	0.09
Ash	1.7
High Heating Value (kcal/kg)	4459

The solvent (IPA and water) was obtained in the laboratory, whereas UCO and ULO were derived from domestic waste and motorcycle workshop refuse. The properties of solvent are described in Table 2.

Table 2. Solvent properties

Solvent	Viscosity, cP	Boiling point, C
IPA	2.4	82.5
Water	10.0	100
UCO	33 - 45	175
ULO	55.86	350-500

2.2. Experimental Setup

The gasification operations were carried out in an updraft fixed-bed gasifier with a capacity of 25 kg/h using air as the gasifying agent. The reactor was outfitted with a screw feeder for feeding feedstock, an air blower for flowing gasifying agent, and a revolving disc for collecting solid residue. To monitor the gasification temperature, three K-type thermocouples were mounted at the gasifier with a distance of 120° apart. The gasifier's airflow was monitored with a vortex flowmeter DN 15 and adjusted with a butterfly valve. The gasification process was operated at a temperature range of 500 – 600°C and 700 – 800°C as presented in Table 3. At 500–600°C, the PKS and air flow rate were maintained at approximately 30 kg/h and 12.50 m^3/h, whereas at 700–800°C, they were maintained at approximately 15 kg/h and 14.50 m^3/h.

Table 3. Gasification operating condition

Temperature range, °C	PKS flow rate, kg/h	Air flow rate, m^3/h
500 - 600	29.06	12.48
	29.56	13.00
	31.40	12.08
700 -800	15.10	14.40
	14.50	14.60
	15.60	14.90

As shown in Figure 2, the gasification system was equipped with a syngas cooling system following the reactor. The syngas cooling system consisted of sequentially arranged scrubbers, elutriators, and heat exchangers. The scrubber and elutriator were employed as the initial cooling system to remove particulate matter that had settled in the water seal at the bottom of this equipment. Then, the syngas was cooled using a one-pass shell and tube heat exchanger to a temperature of approximately 40°C. This system employed a non-contact system, meaning the syngas passing through the equipment did not come into direct contact with the cooling media. To increase the efficiency of tar reduction, the syngas was brought into direct contact with the cleaning media by passing it through a wet scrubber. Two wet scrubbers were installed in series following the cooling system. Various types of solvents, namely IPA, water, UCO, and ULO, were used as tar-dissolving agents or syngas cleaning media. The wet scrubbers were submerged in a water bath containing water, ice cubes, and salt, while the temperature was maintained at 10°C.

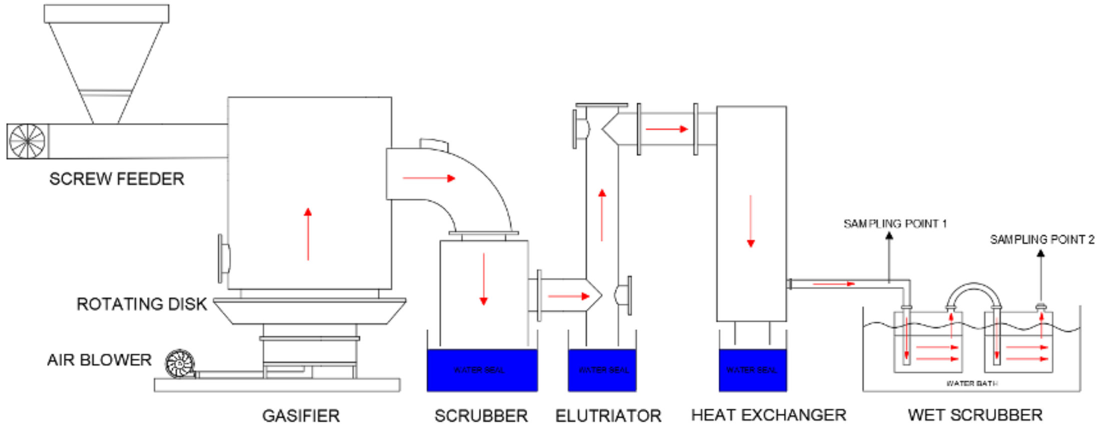

Figure 2. Palm kernel shell gasification with tar removal equipment including cooling system and wet scrubber

The PKS gasification process was conducted at two distinct temperature ranges: 500-600°C and 700-800°C. Gas and tar samples were collected at sampling point 1 for each temperature range. The Programmable Logic Controller (PLC) and Human Machine Interface (HMI) were linked to a thermocouple to ascertain the optimal sample time when the temperature curve exhibited a consistent value. The samples were then examined to determine the optimum operating temperature that yielded gas with the lowest tar concentration. Subsequently, wet scrubbers equipped with various solvents were fitted, and the gasifier was run at the optimum temperature. To assess the effectiveness of tar reduction through the use of a wet scrubber, samples of gas and tar were collected at sampling points 1 and 2.

2.3. Tar and Gas Sampling

Tar elimination efficiency was determined by comparing the syngas tar concentrations at the wet scrubber's inlet and outlet. As shown in Figure 3, the gas and tar sampling instrument were comprised of five impingement tubes through which the syngas was passed (Neeft et al., 2008). The tubes were kept at 10°C by submerging them in a water bath.

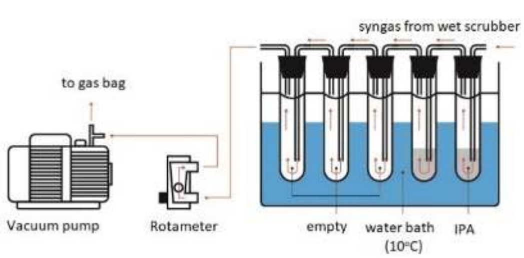

Figure 3. Taking and analyzing gas and tar samples

The gas was then directed through a series of two impinger tubes containing IPA to dissolve the tars. In order to collect the final condensates, the final three tubes were left unfilled. After approximately 20 minutes of gasifier operation, when the gasifier's temperature remained constant, samples of tar were taken from the wet scrubber's inlet and outlet. In every experiment, the syngas was passed through the sampling bottles to collect tar. To determine the tar concentration in the gas, it is necessary to evaporate the solvent in two impinger tubes and weigh the tar residue. Using a vacuum pump, the gas flow rate in the tar sampling device was maintained at 15 L/min for 15 minutes. The syngas is then placed in a gas bag and analyzed using gas chromatography to determine its composition.

3. Results and Discussion

3.1. Effect of gasification temperature on tar production

The gasification operating temperature was observed by installing a thermocouple on the reactor connected to a data logger in the panel box. As presented in Figure 4, the operating temperature continued to rise as the operating time progressed. The gasification reaction occurs for approximately 50 minutes, starting at 30th minute to 80th minutes. During this time, gas samples were taken at sampling point 1 to determine the effect of operating temperature on the tar content of the producer gas.

As the temperature rose, there was a decrease in the tar yield. In the gasification temperature range of 500-600 °C, syngas with a tar yield of 0.173 g/kg of biomass was produced. While in the temperature range of 700-800°C, generate syngas with the tar yield of 0.165 g/kg of biomass. This occurs due to the increase in activity of tar cracking and reforming reactions (Gil-Lalaguna et al., 2014). Similar trend was reported by (Zhang & Pang, 2019) for different type of biomass (corn stover, rice husk, and pine)

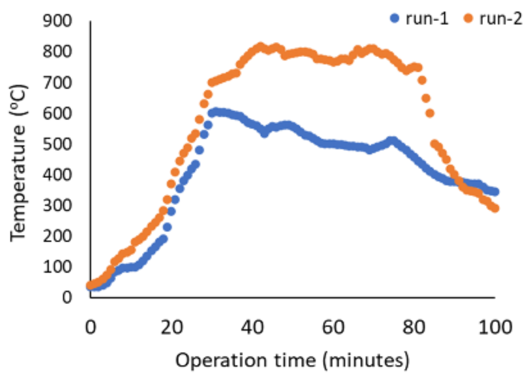

Figure 4. Gasification temperature monitoring

3.2. Tar Removal Performance

The average syngas temperature at the heat exchanger's outlet was 40°C. Due to the extremely low dew point of the tars, some of the tars did not condense in the heat exchanger. So, the syngas coming out the heat exchanger still has high tar content, at 49.40 g/Nm^3. Since the tar is highly soluble in either polar or nonpolar solvents, the syngas departing the heat exchanger was passed through the wet scrubber. Syngas tar concentration can be reduced in the wet scrubber by dissolving the tar constituent. It can be seen in Figure 5, IPA delivers the lowest syngas tar at 0.31 g/Nm^3, followed by water at 4.43 g/Nm^3. While UCO and ULO result in quite high syngas tar, at 17.34 g/Nm^3 and 20.64 g/Nm^3, respectively. This is in contrast to the study conducted by (Ahmad et al., 2016), which found that UCO is the most effective at reducing the tar content of syngas. This phenomenon occurs because the tar content of each biomass's syngas varies, depending on biomass composition (Sikarwar et al., 2016).

As shown in Figure 6, (Waluyo et al.,2018), reported that the majority of the tar components of PKS's syngas are polar compounds including 71.8% phenol, 9.2% guaiacol, and 7.1% acetic acid; only small portion of aromatic component including benzene and toluene. Similar findings were reported by (Zubair Yahaya et al., 2019), who found that PKS syngas tar contained 61.4% phenol, 33.34% aromatics and 2.7% acids. Whereas (Ahmad and Zainal, 2016) found that the majority of tar's constituent from biomass's syngas are non-polar compounds such as benzene, toluene, and naphthalene; only very small portion of polar compound, which is phenol at 0.09%.

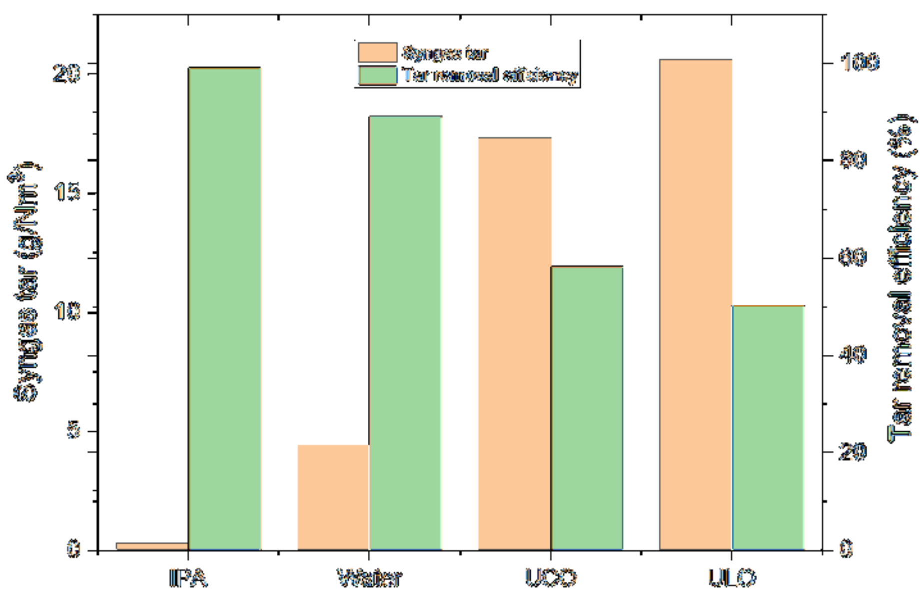

Figure 5. Tar removal performance with various solvent.

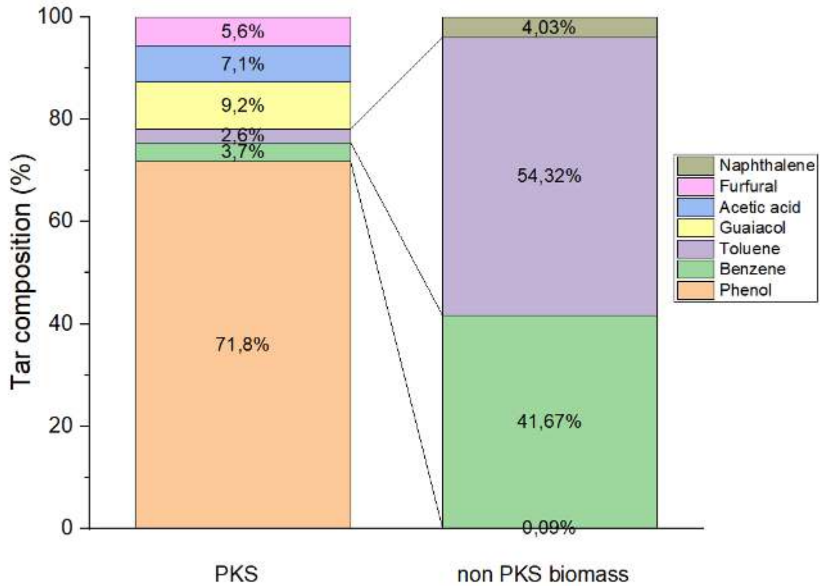

Figure 6. Comparison of syngas tar composition between PKS and non PKS biomass

This occurs because there are two different paths for the creation of PAH. One of these pathways considers benzene to be the precursor, whereas the other pathway considers phenol. Benzene can be synthesized through the initial thermal decomposition of lignin or by the combination of light alkenes via dehydrogenation and Diels-Alder condensation processes. Phenol is produced through the cleavage of the ether linkage in lignin under acidic circumstances (Qin et al., 2015; Yu et al., 2014). It is found that the efficiency of tar reduction by IPA is higher than water which has a higher polarity. This occurs because IPA is both polar and slightly non-polar, allowing it to dissolve non-polar tars components such as benzene and toluene. The viscosity of the solvent also influences the tar reduction efficiency. According to Table 2, IPA has the lowest viscosity of all solvents. Consequently, when the syngas is fed to the wet scrubber, a larger oscillation occurs which increases the mass transfer of tar to the solvent.

3.3. Syngas Heating Value

The low heating value (LHV) of syngas is affected by burnable components present in syngas, such CH hydrocarbon, hydrogen (H), and carbon monoxide (CO). The LHV calculated based on the following equation (Li et al., 2004)

$$LHV = 10.79\, y_{H_2} + 12.60\, y_{CO} + 35.86\, y_{CH_4} \quad (1)$$

The present study produces syngas with LHV in the range of 5 – 6 MJ/Nm^3. These results are identical to the 5.3 MJ/Nm^3 syngas produced by a olive kernel gasification with similar cleaning system (Margaritis et al., 2012), and the 5.17 MJ/Nm^3 syngas generated by hardwood chips gasification (Shah et al., 2010).

4. Conclusion

In this study the combination of two methods (in-situ and ex-situ) for tar reduction of PKS's syngas was investigated. The in-situ method applied with variation of gasifier temperature, while the ex-situ method executed with the a-two series wet scrubber. Various types of solvents with different polarities are used in the wet scrubbers. The result show that the lowest tar syngas produced at temperature of 800ºC with IPA as a solvent. This occurs because the higher the temperature, the more primary tar cracks into secondary tar, which is mostly constituted of phenol. The study reported that the lowest tar syngas concentration is 0.31 g/Nm^3. Therefore, the syngas produced from PKS gasification can be supplied to a gas compressor with a maximum permissible tar level of 0.5 g/Nm^3.

Author Contributions

Conceptualization, F.A.P., S.H.P.; Formal analysis, F.A.P.; Investigation, F.A.P., L.N.H., A.T.B.; A.K.; Project administration, H.N.; Supervision, J.W.; Writing – original draft, F.A.P.; Writing – review and editing, F.A.P.

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Data Available Statement

Available on request to the corresponding author.

Conflict of Interest

The author declares that there is no conflict of interest regarding the publication of this manuscript.

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