Improvement of Tar Removal Performance in Biomass Gasification Using Fixed-Bed Biomass Filtration

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Highlights:

- Three types of biomass filters were tested for tar removal.
- Biomass media thickness was found to affect tar removal efficiency.
- Biochar gave the best results of tar removal.

Abstract. Several studies have proven the efficiency of gasification as a thermal process in terms of material decomposition and chemical energy. Synthetic gas (syngas) is a gasification product that can be used as an energy source. However, it needs to undergo treatment to remove the tar content, which could cause several issues in the combustion system. Tar removal can be conducted through biomass filters. In this study, three types of filters were investigated: biochar, rice straw, and rice husk filters. Three thicknesses of the porous media (30, 40, and 50 cm) were investigated. The results revealed that porous media thickness significantly affects tar removal efficiency, as the efficiency was found to increase with the thickness. Biochar was proven to be the best filter media among the three types, with a tar removal efficiency of 59.45% at a thickness of 50 cm.

Keywords: *adsorption; biomass gasification; biomass filter; pressure drop; tar removal.*

1 Introduction

Gasification is a thermochemical process in which a carbonaceous feedstock is converted using gasifying agents to a synthetic gas (H_2, CO, CO_2, and CH_4) and other contaminants (light hydrocarbon, tar, char, and ash) [1,2]. Synthetic gas, or syngas, is a combustible gas produced by gasification. However, it needs to be treated before being used as energy source, because it contains tar, which could foul the system as it condenses and polymerizes at low temperatures [3,4]. Moreover, large amounts of tar in syngas could decrease the performance of the internal combustion engine and increase the difficulty and cost of its maintenance [5]. The tar classification according to the Energy Research Centre in the Netherlands (ECN) is shown in Table 1 [6].

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Table 1 Tar classification according to the energy research centre in the Netherlands.

Tar classification	Definition
Class 1	Tar that gets detected by gas chromatography. Consists of a poly-aromatic hydrocarbon (PAH) that has more than 7 rings. It is usually named heavy tar or gravimetric tar.
Class 2	Heterocyclic compounds; water-soluble hydrocarbons, such as phenol, pyridine, and cresol.
Class 3	Aromatic compounds; one-ring aromatic hydrocarbons that do not cause condensation or solubility problems, such as benzene, toluene, xylene, and styrene.
Class 4	Light polyaromatic compounds; two- and three-ring aromatic hydrocarbons, which condense at relatively high concentration and moderate temperature, such as indene, naphthalene, phenanthrene and anthracene.
Class 5	Heavy polyaromatic compounds; derived from four- to seven-ring aromatic hydrocarbons and condensed at low concentrations and high temperatures, such as pyrene, fluoranthene, and chrysene.

Tar produced by gasification is classified into three types – primary, secondary, and tertiary – according to the production process. Tar formation occurs because of solid carbon breaking down from biomass, as described in the figure above. Primary tar is formed during the pyrolysis stage and depends on the biomass gasification process in the reactor. Primary tar is produced from the pyrolysis of cellulose and hemicellulose components, which contain high amounts of oxygen atoms. Therefore, the primary product of the cellulose and hemicellulose components is oxidized to organic compounds such as alcohol, aldehydes, ketones, carboxylic acids, and heterocyclic aldehydes [7], where products from lignin are considered to be pioneers in the formation of PAHs such as phenols, cresols, catechols, and guaiacols because of their aromatic form [8].

In the oxidation stage, the temperature rises above 500 °C. The oxidized primary tar produces more gas and forms a secondary tar. Secondary tars are mono- and di-aromatic alkylations such as pyridine, furan, dioxin and thiophene [9]. At temperatures over 800 °C, tertiary tars such as benzene, naphthalene, phenanthrene, pyrene and benzoprene are formed.

Tertiary tar appears when the main tar is completely converted into secondary tar [10]. The tar content and composition depend on the operating conditions and the feedstock used. Tar can be removed from syngas by using two types of methods: the primary method, which involves tar reduction inside the reactor [11], and the secondary method, which involves tar reduction outside the reactor [12].

The secondary method includes using filters to reduce tar through adsorption on the surface of filter porous media. Thapa, *et al*. conducted a study on tar reduction by using wood chips, obtaining a tar removal efficiency of 10.28% [13]. Paethanom, *et al.* conducted a study using rice husk and its ash (biochar) as the porous media, resulting in efficiencies of 60% and 87.5%, respectively [14].

Awais, *et al.* performed a set of experiments using wood chips and corncobs as the porous media, in which the tar removal efficiencies were 74% and 71%, respectively [15]. Furthermore, research has been done that focused on biomass media thickness and how a filter can condense tar, not only adsorb it.

In this study, an adsorption method by passing syngas through a biomass filter was employed to reduce the tar content in the syngas. The porous media used were biomass waste, i.e. biochar, rice straw, and rice husk. Typically, in biomass filters, the increase in pressure drop changes the syngas flowrate, which causes the tar to accumulate in the filter [13].

Rice straw and rice husk were chosen because of their abundance and availability, while biochar was chosen for its proven ability to remove tar. Different thicknesses of porous media (30, 40, and 50 cm) were used in all cases. The efficiencies of tar reduction with filters containing biochar, rice straw, and rice husk were determined and compared.

2 Methodology

2.1 Experimental Setup

The experimental setup used in this study is shown in Figure 1. The setup is divided into two main parts: a fixed-bed down-draft biomass gasification system and a measuring instrument. The fixed-bed down-draft biomass gasification system comprised a reactor, cyclone, water condenser, biomass filter, air blower, ring blower, and cyclone burner.

The experiment was conducted at standard ambient temperature and pressure (temperature 25 °C and pressure 1 atm). It had a running capacity of 10 kg feedstock per hour. The measuring instrument comprised thermocouples, a digital manometer (Digital Manometer Dwyer 475-00-FM), and a tar protocol module. The thermocouples were connected to a data acquisition system (ADVANTECH DAQ USB-4718) to view the results. The digital manometer helped to measure the pressure difference through orifices set up in the gasification system. The tar protocol module used to measure the tar content followed the ECN-C-06-046 standard set by the ECN.

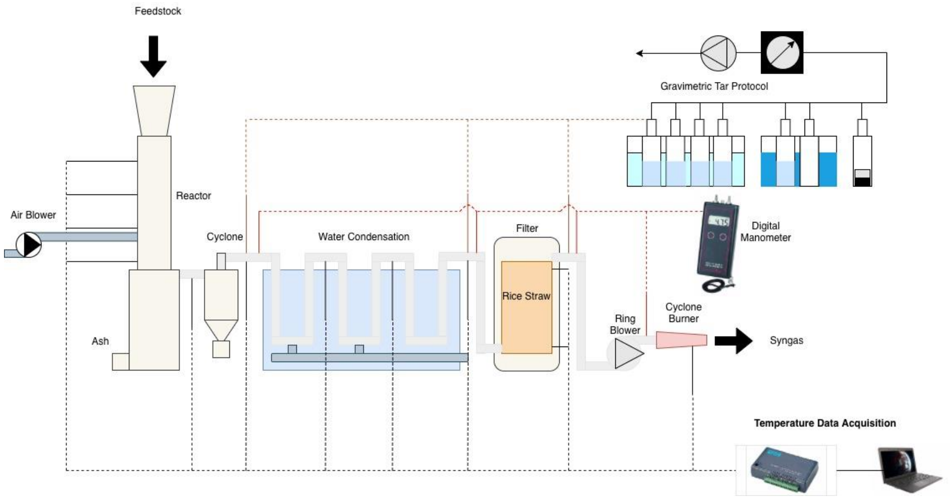
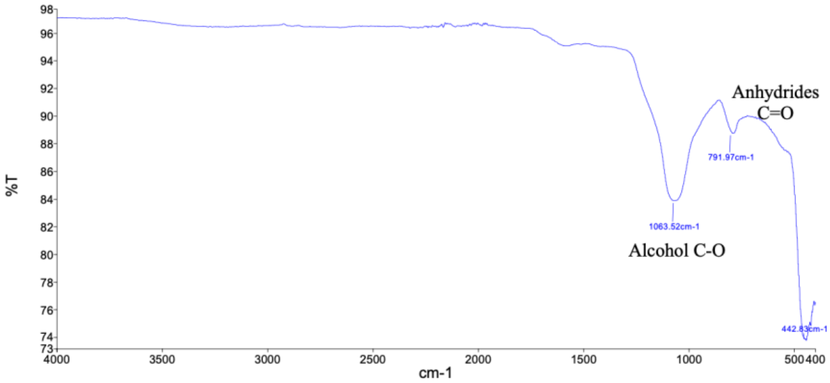


Figure 1 The experimental setup used in this study.

2.2 Brunauer-Emmett-Teller and Fourier-Transform Infrared Spectroscopic Analyses

First, all porous media, as shown in Figure 2, were tested using the Brunauer-Emmett-Teller (BET) method and Fourier-transform infrared (FTIR) spectroscopy to determine their specific surface area and compound composition, respectively, before initiating the experiment. Surface area was used as the parameter to test the adsorption ability, because each medium has a different surface area. While the composition of compounds related to the bonding process of tar compounds in the syngas is shown in Figure 3.

Figure 2 Ground porous media: biochar (left); rice straw (center); and rice husk (right).



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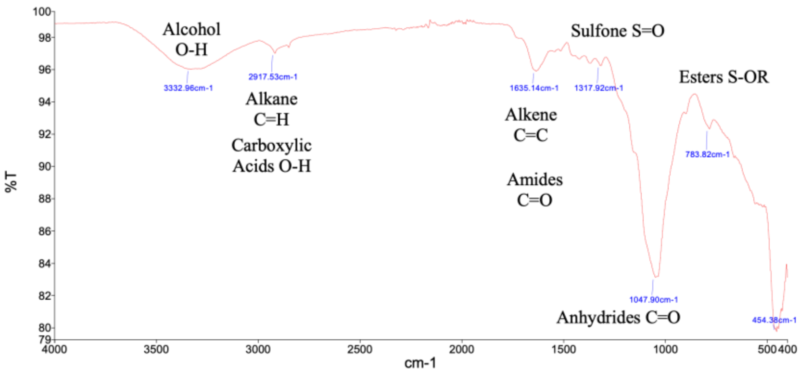

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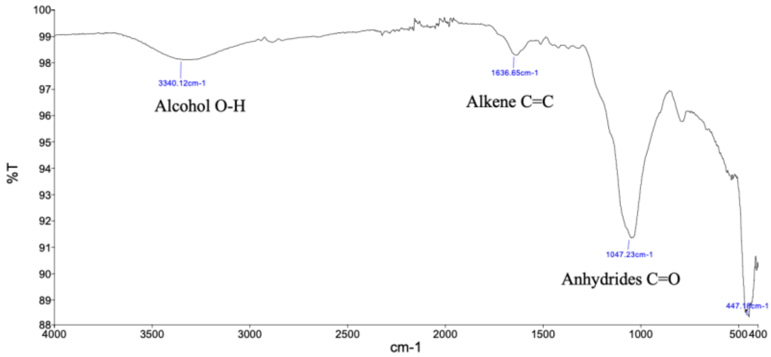


(c)

Figure 3 Fourier-transform infrared spectroscopic results for three types of porous media: (a) biochar; (b) rice straw; and (c) rice husk.

2.3 Tar Protocol Module

Measurements were conducted in accordance with the UNI EN 15439-2008 standard. The protocol followed for the measurements is provided in Figure 4. Acetone was used as the solvent for dissolving the tar during the measurements. Seven impinger bottles were used for collecting samples and measuring the tar content in the syngas.

The solvent was poured into six bottles, of which four were placed inside a well-insulated box containing water at 20 °C and two were placed inside another well-insulated box containing water at −20 °C. A filter was placed inside the last bottle (with no solvent), which was also filled with active carbon to further reduce the tar content in the syngas and enhance the measuring accuracy.

The tar measurements began 10 minutes after the gasification system was started and ended after 15 minutes of recording, as can be seen in Figure 5 for the timeline of the tar protocol. Three models were studied, labeled as the first model, with biochar as the porous media; the second model, with rice straw as the porous media, and the third model, with rice husk as the porous media. The configuration used for each of the models is detailed in Table 2.

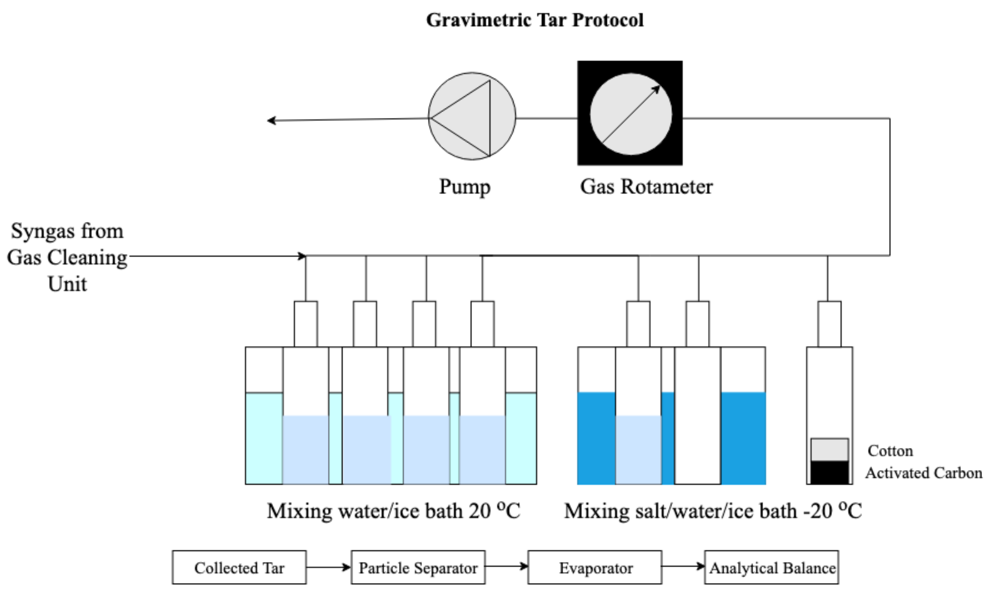


Figure 4 Tar sampling procedure.

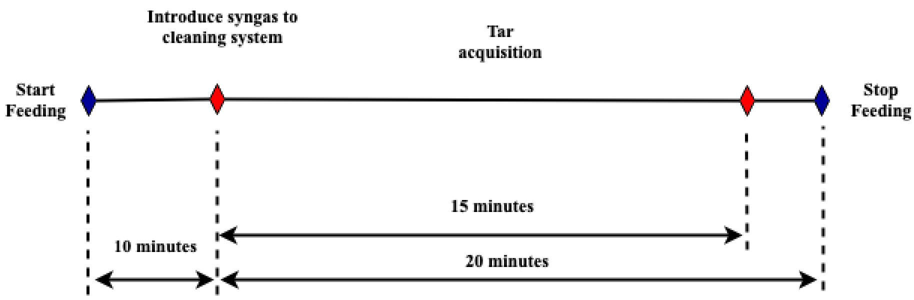


Figure 5 The measuring timeline in the study.

Table 2 Properties of the Media Used in the Experiment

Model	Porous media	Variations of porous media height (cm)	Bulk Density (g/cc)	Porosity (%)	Grain mass (g)	Surface area (m^2)
1st	Biochar	30	0.126	51.87	3,336.13	15,940.01
		40		35.83	4,106.00	19,618.47
		50		19.79	5,132.50	24,523.09
2nd	Rice straw	30	0.095	89.68	291.00	3,124.47
		40		86.24	388.00	4,165.96
		50		82.80	485.00	5,207.45
3rd	Rice husk	30	0.215	47.72	1,800.00	9,165.60
		40		35.66	2,400.00	12,220.80
		50		19.58	3,000.00	15,276.00

3 Results and Discussion

3.1 First Model: Biochar Filter

Several studies have reported the effectiveness of biochar in reducing the tar content in syngas. Biochar contains activated carbon, an important component for catalytic conversion. However, its action efficiency in reducing tar content depends on its characteristics and ambient conditions, such as temperature [17]. The biochar used in this study came from residual gasification of rice husks. The results of the BET analysis are shown in Table 2. Of all the porous media used in the study, rice straw had the highest specific surface area (10.737 m^2/g), followed by biochar (5.092 m^2/g) and rice husk (4.778 m^2/g). The results of the FTIR spectroscopic analysis are shown in Figure 3.

The results revealed the following compositions of the porous media: the biochar consisted of alcohol and anhydrides; the rice straw consisted of alcohol, carboxylic acids, alkanes, alkenes, amides, sulfones, anhydrides, and esters; and the rice husk consisted of alcohol, alkenes, and anhydrides. The key components of the media were alcohol, which effectively dissolves tar; anhydrides, which create lignocelluloses, and alkanes. All three components are effective in the adsorption of polyaromatic hydrocarbons (PAHs) of class 1 and class 5 tars.

In this study, the biochar devolatilization removed all the hydrocarbon compounds, leaving behind only alcohol and anhydrides, important constituents required for tar adsorption. The biochar medium was stacked loosely to see the adsorption capability of the media. This is important because if it is stacked tightly it will make the adsorption between the particles of the biochar medium ineffective.

The thicknesses of the porous media were found to affect tar removal efficiency of the filters. This is because the total surface area increases with the increase in volume of porous media, consequently increasing the tar adsorption. In addition, pressure changes that occur along the filter greatly affect the adsorption residence time, so the longer the thickness of the trajectory, the higher the amount of adsorbed tar.

Of all the thickness configurations, as shown in Figure 6, thickness 1 (30 cm) had the lowest pressure drop (0.142 kPa). This was because the inlet flow passed through a smaller volume of the porous media, resulting in a negligible pressure loss. As can be seen in Figure 7, thickness 1 also had the lowest tar removal efficiency (33.7%), which can be attributed to the low pressure drop. Thickness 2 (40 cm) had higher tar removal efficiency (48.63%) than thickness 1, because of the increase in total surface area.

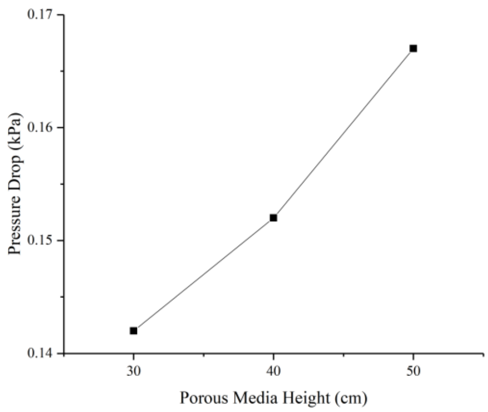


Figure 6 Pressure drop across biochar porous media.

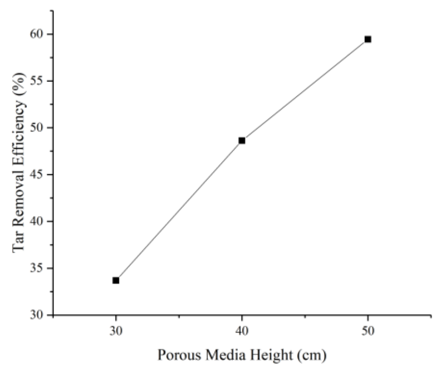
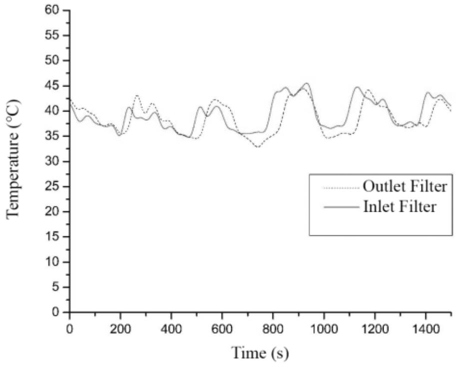


Figure 7 Tar removal efficiency at different thicknesses of biochar porous media.

This configuration had a noticeable pressure drop (0.152 kPa), indicating a more effective adsorption process than that of thickness 1. Thickness 3 (50 cm) exhibited the highest tar removal efficiency (59.45%), because of the maximum total surface area. In addition, this configuration had the highest pressure drop (0.167 kPa) compared to thicknesses 1 and 2, indicating the superior effectiveness of the adsorption process in reducing tar in the syngas.

For the 30-cm thickness of the biochar (Figure 8(a)) it can be seen that syngas temperatures continued to rise but not significantly. The fluctuations that occurred were quite large due to quick changes in the operational conditions. The average temperature reduction for the 30-cm thick biochar medium was 2.08 °C. For 40-cm thick biochar medium (Figure 8(b)) it can be seen that the syngas temperatures continued to increase significantly. As noted above, the fluctuations that occurred were quite large due to fast changes in the operational conditions. The average temperature reduction in the 40-cm thick biochar medium was 3.15 °C. The temperature reduction in the biochar medium of 40 cm thickness was higher than in the rice husk medium with the same thickness. In the 50-cm thick biochar medium (Figure 8(c)), the syngas temperature did not increase significantly.

The fluctuations that occurred were very small because the operational conditions occurring in the reactor were quite stable. The average temperature reduction in the 50-cm thick biochar medium was 4.73 °C. The temperature reduction was the highest in the 50-cm thick biochar medium compared to the other medium variations. The decrease in temperature in the filter was greatly influenced by the thickness, where the adsorption process will take longer. The old adsorption effect will make the temperature decrease because there is also a process of transferring heat from the tar particles into the medium [14]. Besides that, alcohol and anhydride compounds can well adsorb phenol compounds and polyaromatic hydrocarbon compounds [18].



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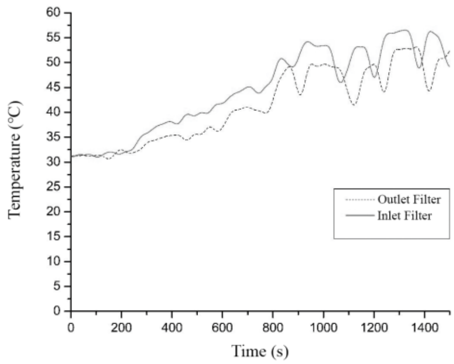

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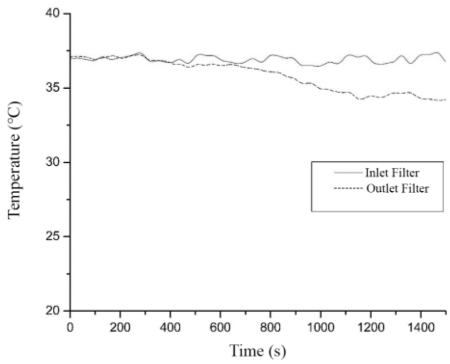


(c)

Figure 8 Graph of temperature decrease versus biochar medium thickness: (a) 30 cm; (b) 40 cm; and (c) 50 cm.

3.2 Second Model: Rice Straw Filter

Rice straw has a hydroxyl structure that enhances moisture adsorption in syngas [12]. In addition, it has sulfones, which help to reduce moisture, and silica, which increase the tar adsorption from the syngas [19]. Rice straw is also able to significantly reduce incondensable tar (classes 1, 4, and 5) [12], while biochar significantly reduces all tar classes. Similar to biochar, the efficiency of rice straw increased with an increase in thickness. The tar removal efficiency at thicknesses 1, 2, and 3 (30, 40, and 50 cm, respectively) were 29.47%, 47.42%, and 52.38%, respectively, attributed to the increase in pressure drop (as seen in Figure 9) and total surface area (as shown in Figure 10).

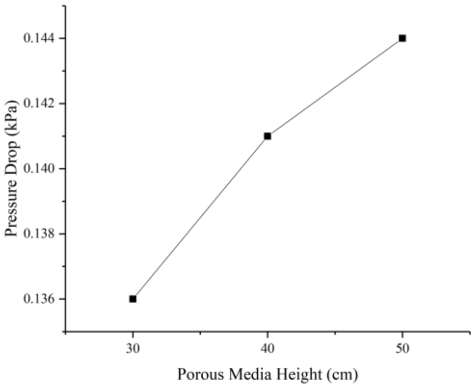


Figure 9 Pressure drop across rice straw porous media.

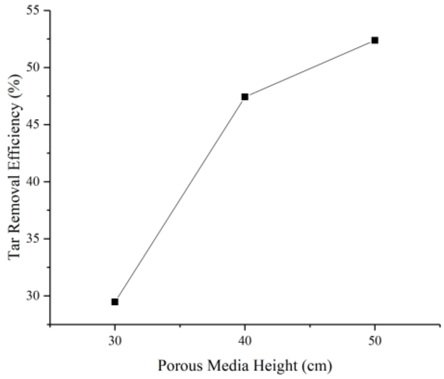
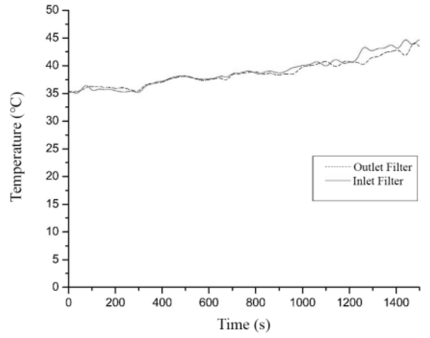


Figure 10 Tar removal at different thicknesses of rice straw porous media.

For the 30-cm thick rice straw medium (Figure 11a) it can be seen that the syngas temperatures continued to rise but not significantly. There was a decrease in average temperature for the 30-cm thick rice straw medium at 0.30 °C. For the 40-cm thick rice straw medium (Figure 11(b)) it can be seen that the syngas temperatures continued to rise but not significantly, the same as for the 30-cm thick rice straw medium. The fluctuations that occurred were very large due to very quick changes in the operational conditions every second. The average temperature reduction in the 40-cm thick straw medium was 1.12 °C. For the 50-cm thick rice straw medium (Figure 11(c)) it can be seen that the syngas temperatures continued to increase significantly. The fluctuations that occurred were minimal at the beginning of data recording. This was due to the fact that the operational conditions did not change rapidly.

The decrease in temperature at the outlet was highest compared to that of the 30-cm and 40-cm thick straw medium because the surface area of the 50-cm thick straw medium was the highest compared to that of the 30-cm and 40-cm thick rice straw medium.



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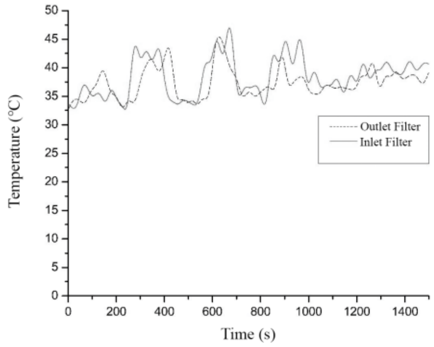

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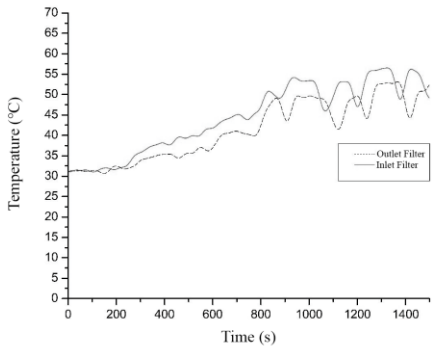


(c)

Figure 11 Graph of temperature decrease versus rice straw medium thickness: a) 30 cm; b) 40 cm; and c) 50 cm.

The average temperature reduction for the 50-cm thick straw medium was 4.45 °C. Sulfones and esters (which rice straw contains) made the adsorption slow down, because these compounds have non-hydroxyl properties [20]. Regarding the rice straw medium, although thickness 3 (50 cm) showed the highest tar removal efficiency, the increase in efficiency from that achieved with thickness 2 was not significant compared to the difference made by increasing the straw thickness from 30 to 40 cm (thickness 1 to thickness 2, respectively).

The significant tar removal performance shown in Figure 10 was caused by chain adsorption related to the sulfone structure, which effectively adsorbed class 2 tar (which has the second highest tar content after class 1 tar) [19]. The pressure drop increase was not significant, which may be attributed to the shape limitation of the rice straw.

3.3 Third Model: Rice Husk Filter

Rice husk contains high levels of silica and therefore can be efficiently used for tar adsorption [21]. Rice husk also contains alcohol and anhydrides, which are reported to perform well in PAH adsorption (tar class 1). As a filter material, rice husk performs well, achieving an efficiency of 60% [14]. Similar to the other media models used in this study, the tar removal efficiency and pressure drop showed an increasing trend with increase of the porous media thickness (thicknesses 1, 2, and 3). The increase in efficiency (26.06%, 40.13%, and 56.65%, respectively) can be attributed to the increase in total surface area and pressure drop (0.137, 0.145, and 0.15, respectively), which can be seen in Figures 12 and 13.

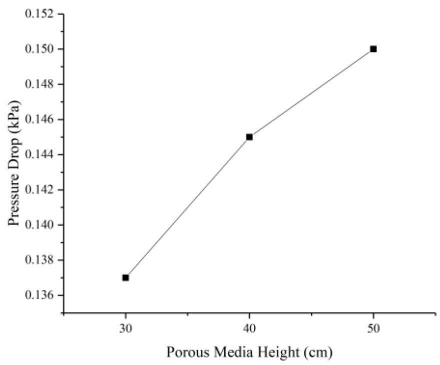


Figure 12 Pressure drop across rice husk porous media.

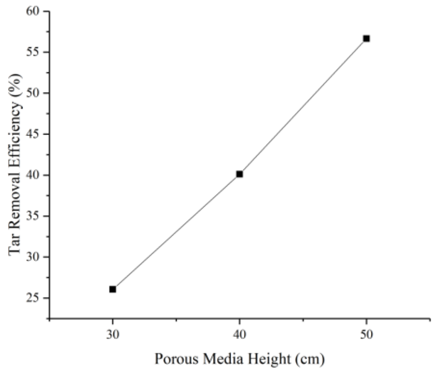


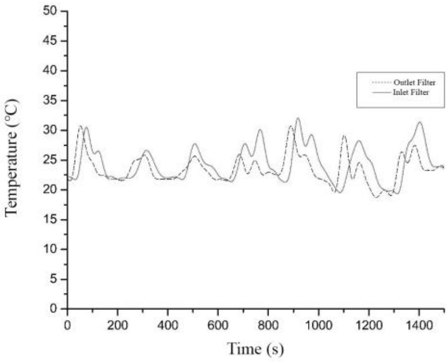
Figure 13 Tar removal efficiency at different thicknesses of rice husk porous media.

For the 30-cm thick rice husk medium (Figure 14(a)) it can be seen that the syngas temperatures continued to rise but not significantly. As has already been explained, this temperature increase was charged by the accumulation of heat from the reactor. There was a decrease in average temperature for the 30-cm thick rice husk medium of 1.87 °C.

The temperature reduction at a thickness of 40 cm (Figure 14(b)) at the outlet was higher than that of the 30-cm thick rice husk medium because the surface area of the 40-cm thick rice husk medium was higher than that of the 30-cm thick rice husk medium. However, it was found that the temperature decrease at the outlet decreased also because of accumulating tar attached to the surface of the medium, reducing the medium's ability to deliver high syngas temperatures.

There was a decrease in average temperature in the 40-cm thick rice husk medium by 3.01 °C. The syngas temperatures continued to display a very significant increase at 50-cm thickness (Figure 14(c)). As already explained, this temperature increase is due to the accumulation of heat from the reactor. There was a decrease in average temperature for the 50-cm thick rice husk medium by 4.45 °C.

Alkenes (which rice husk contains) made the adsorption slow down, because these compounds can hamper the adsorption process [21].In contrast with the rice straw medium, thickness 3 of the rice husk medium showed a significant increase in removal efficiency compared to thickness 2. This was also the case for the increase in pressure drop, which showed an increase from 0.145 to 0.15 kPa.



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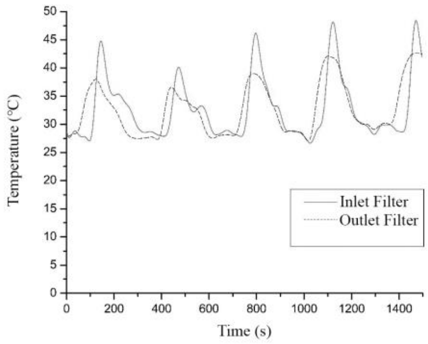

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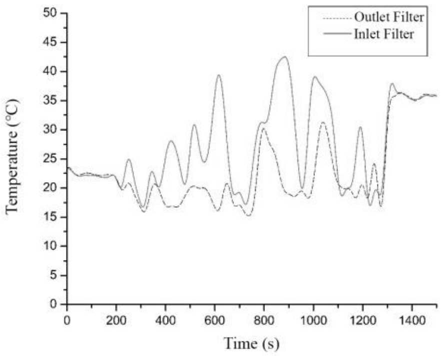

(c)

Figure 14 Graph of temperature decrease versus rice husk medium thickness: a) 30 cm; b) 40 cm; and c) 50 cm.

3.4 Comparison between the Three Materials

A comparison between the tar removal efficiencies of the three models is shown in Figure 15. The highest possible tar removal efficiency in the first, second, third models (using biochar, rice straw, and rice husk medium) reached 59.45%, 52.38%, and 56.65% at 50 cm, respectively. These results suggest that biochar is the most suitable porous media for reducing tar. The highest tar removal efficiency of biochar can be attributed to its constituents, which are key ingredients (i.e. activated carbon, alcohol, and anhydrides) with excellent tar reduction capabilities [14]. The correlation between pressure drop and tar removal efficiency, which confirms that an increase in pressure drop can lead to an increase in tar removal efficiency, is detailed in Figure 16.

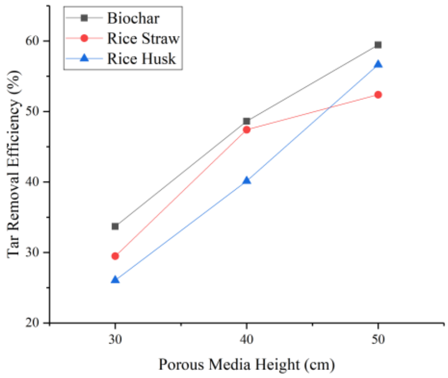

Figure 15 Comparison between the three types of porous media.

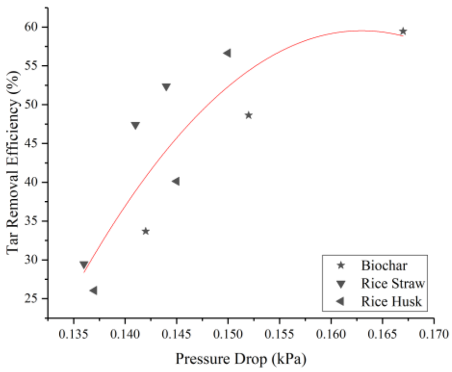

Figure 16 The relationship between pressure drop and tar removal efficiency.

This can be explained using Boyle's law, which states that when the pressure increases/decreases, the temperature consequently increases/decreases. Therefore, the temperature of the syngas decreases with its pressure until the tar dewpoint is reached. When the dewpoint is reached, the tar condenses, which facilitates the adsorption process.

It can be concluded from Figure 17 that there is a relationship between the surface area of the filter media used and the syngas temperature reduction at the filter outlet. The greater the surface area of the filter medium, the greater the reduction in temperature syngas [22]. This is in accordance with the principle of heat transfer, especially the principle of conduction (the larger the surface area, the greater the area of the filter medium that contacts with the syngas). The surface area is directly proportional to the decrease in syngas temperature.

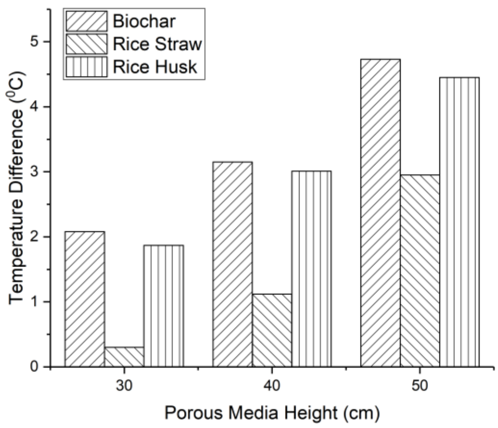

Figure 17 The relationship between porous media height and temperature difference.

4 Conclusion

The results of this study revealed that the thickness of the porous medium and the pressure drop significantly affect the tar removal efficiency. The tar removal efficiencies of the three types of porous media (biochar, rice straw, and rice husk) used in the filter showed an increasing trend with their thicknesses. The highest tar removal efficiencies of biochar, rice straw, and rice husk filters were 59.45%, 52.38%, and 56.65%, respectively, at a thickness of 50 cm. The biochar filter showed the best performance among these three types.

Acknowledgment

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