



Char and char-supported nickel catalysts for secondary syngas cleanup and conditioning

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ABSTRACT

Tars in biomass gasification systems need to be removed to avoid damaging and clogging downstream pipes or equipment. In this study, Ni-based catalysts were made by mechanically mixing NiO and char particles at various ratios. Catalytic performance of the Ni/char catalysts was studied and compared with performance of wood char and coal char without Ni for syngas cleanup in a laboratory-scale updraft biomass gasifier. Reforming parameters investigated were reaction temperature (650–850 °C), NiO loading (5–20% of the weight of char support), and gas residence time (0.1–1.2 s). The Ni/coalchar and Ni/wood-char catalysts removed more than 97% of tars in syngas at 800 °C reforming temperature, 15% NiO loading, and 0.3 s gas residence time. Analysis of syngas composition indicated that concentrations of H₂ and CO in syngas significantly. Furthermore, performance of the Ni/coalchar catalyst was continuously tested for 8 h. There was slight deactivation of the catalyst in the early stage of tar/syngas reforming; however, the catalyst was able to stabilize soon after. It was concluded that chars especially coal char can be an effective and inexpensive support of NiO for biomass gasification tar removal and syngas conditioning.

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1. Introduction

Biomass gasification is considered one of the most promising technologies for production of sustainable fuels [1–4]. Biomass gasification is a process in which biomass undergoes incomplete combustion to produce a gas product called syngas that consists mainly of H₂, CO, CH₄, CO₂, and N₂ (if air is used in combustion) in various proportions. Biomass gasification has many advantages over direct combustion. It converts low-value feedstocks to high-quality combustible gases, which can be not only directly burned or used for electricity generation but also turned into liquid transportation fuels [5]. However, tars are produced along with syngas during biomass gasification and their contents vary from about 0.5–100 g/m³ depending on the type and design of the gasifier, feedstock used, and operating conditions [6]. Tar is a generic term comprising all organic compounds present in syngas except gaseous hydrocarbons. Tars can condense to more complex structures in pipes, filters, or heat exchangers of downstream equipment and processes, which may cause mechanical breakdown of the entire system. Tars may also deactivate catalysts in the refining process. It is essential to reduce the level of tars to enable widespread utilization of syngas. Several approaches for tar removal, such as physical treatment [7,8], thermal cracking [9], plasma-assisted cracking [10], and catalytic reforming [11,12], have been reported

in the literatures. Among these, catalytic reforming is considered the most promising in large-scale applications because of its fast reaction rate and reliability [13] and its ability to increase the quantity of useable gases such as CO and H₂ in syngas.

Various types of catalysts such as calcined rocks [14], zeolites [15], iron ores [16], alkali metals [17], Ni-based catalysts [18], and precious metals [19] have been studied for their usefulness in tar removal in biomass gasification. For catalytic reactivity and economic reasons, Ni-based catalysts are considered the most promising for tar removal and syngas reforming [20–23]. Nickel catalysts are usually supported by metal oxides (e.g., Al₂O₃ and MgO) or natural materials (e.g., dolomite, olivine, activated charcoal) [24–29]. These supports are relatively expensive, and the catalyst preparation steps involving impregnation and calcination are time and energy consuming; these factors limit extensive application of Ni-based catalysts. As a promising alternative, chars have been reported to be an inexpensive catalyst with fair performance in tar removal [30–33] and also an excellent adsorbent [34]. This pioneering research investigated catalytic performance of a new catalyst called Ni/char, which was made by mechanically mixing char particles and NiO powders. This catalyst is unique in that char serves as an inexpensive support and also a catalyst and that no impregnation or calcination steps are needed in catalyst preparation.

The objectives of this study were (1) to examine the feasibility of using chars as the Ni catalyst support while the chars also serve as a catalyst themselves and (2) to determine the effect of

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operating parameters (i.e., catalytic reaction temperature, gas residence time, and NiO loading) on tar removal rate and syngas composition. The new catalyst, Ni/char, was made by mechanically mixing Ni particles with wood char and coal char particles separately. The char-supported Ni catalysts were tested in a laboratory-scale updraft biomass gasifier. Chars without Ni were also studied as the baseline for comparison.

2. Materials and methods

2.1. Catalyst preparation and characterization

Four types of catalysts were prepared and studied: wood char, coal char, wood char with NiO (Ni/woodchar), and coal char with NiO (Ni/coalchar). The wood char and coal char were obtained from Royal Oak Enterprises, Inc. (Omaha, AR). Chars were crushed and sieved to obtain particles in the size range of 40–60 meshes (0.3–0.45 mm). The porous char support provides an excellent medium for adhesion of the micro-NiO particles. Nickel oxide powders (AC41558, density 6.67 g/ml) were purchased from Fisher Scientific (Pittsburgh, PA). The Ni/woodchar and Ni/coalchar catalysts were prepared by mechanically mixing char particles and NiO particles in a transparent glass beaker at desired ratios of NiO to char weight (5–20% at steps of 5%).

All Ni catalysts were scanned with a HITACHI S-3500 N scanning electron microscope (SEM; Hitachi, Ibaraki, Japan) and an EDX (energy dispersive X-ray) measurement was conducted. For more detailed characterization of the catalysts, hydrogen chemisorption was performed to determine Ni dispersion rate and specific surface area and diameter of sphere crystallites using a Zeton Altamira AMI-200 unit (Altamira Instruments, Pittsburgh, PA). Hydrogen chemisorption method was previously used to investigate Ni distribution on activated carbons by some other researchers [35,36]. This method was adopted in this study considering the similarity between activated carbon and chars. The catalyst (0.1 g) was loaded in a U-shaped quartz reactor fitted with a thermocouple for continuous temperature measurements. Thermal treatment of samples was conducted with 10% H₂/argon at a flow rate of 50 ml/min and a heating rate of 10 °C/min up to 800 °C.

The treatment was holding for 60 min at 800 °C then the catalyst was flushed for 2 h with argon after the temperature of the catalyst returned to room temperature. After that, a flow of 10% H₂/Ar was injected into the reactor every 2 min. H₂ consumption was monitored by a thermal conductivity detector.

2.2. Apparatus and experimental parameters

The experimental system was composed of three subsystems: (1) biomass gasifier system, which provided a constant flow of raw syngas at a specific flow rate to the reforming unit via control of a flow control valve and vacuum pump; (2) tar reforming unit; and (3) tar collection unit. A schematic diagram of the system is shown in Fig. 1, and details of each subsystem are presented in the following sections.

2.2.1. Biomass gasifier system

Gasification of sawdust was carried out in a laboratory-scale updraft biomass gasifier system, which consists of a reaction chamber, gas cooler, and blower assembly. The gasifier has an overall syngas production rate of 5–50 ft.³/min depending on the voltage to the 15-W blower, which is used to blow air from the bottom of the gasifier into the reaction chamber. The raw syngas produced flows into the gas cooler, in which steam and a fraction of tars condense and are collected. In gasification tar reforming experiments, a small fraction of the syngas from the outlet on the top of the gas cooler was directed to the reforming tube, and syngas flow rate was measured with a gas flow meter (Brooks Instrument, Hatfield, PA). Average composition and tar content of the raw syngas of five replications from the sampling port after the syngas cooler are presented in Table 1. All values of tar removal rates in this article were calculated based on the already condensed syngas and reflect only the contribution of reforming reactions to tar removal.

2.2.2. Tar reforming unit

The tar reforming system included a quartz, 1-in.-diameter, 24-in.-long reactor tube with a complete vacuum-sealing assembly (MTI Corporation, Richmond, CA) and a Thermolyne Economy

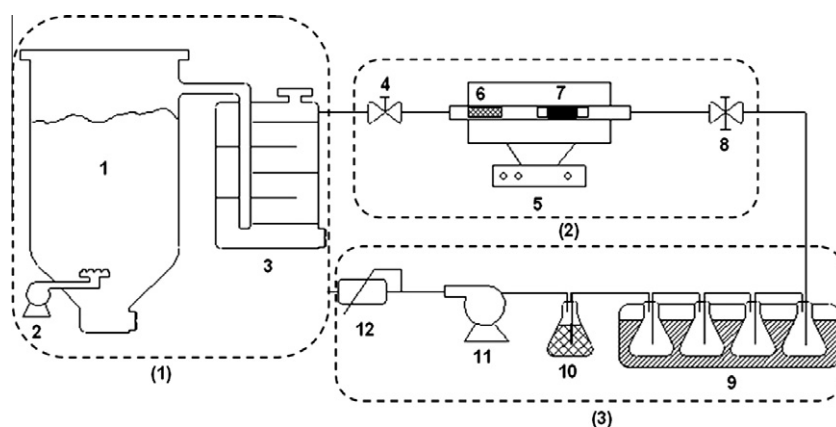


Fig. 1. Schematic diagram of the experimental system (1 – gasifier chamber; 2 – blower; 3 – gas cooler and burner; 4 – switch; 5 – tube furnace; 6 – alumina foam filter; 7 – catalyst bed; 8 – flow control valve; 9 – tar sampling unit; 10 – moisture adsorbent; 11 – vacuum pump; 12 – gas flow meter).

Table 1
Composition of raw syngas from the sampling port after the syngas cooler.

Contents of gaseous components of original syngas (vol.%)					Tar content (g/m ³)
N ₂	H ₂	CO	CO ₂	CH ₄	
49.71	23.97	22.95	1.06	2.32	8.55

Table 2
Experimental parameters of tar reforming.

Condition	Parameter
Gasification agent	Air
Biomass feed	Sawdust
Catalytic bed temperature (°C)	650–850
Gas residence time (s)	0.1–1.2
Ni loading in catalysts (%)	0–20
Gas flow rate (l/min)	9.12
Reforming time (min)	15
Char particle size, mesh (mm)	40–60 (0.3–0.45 mm)
Catalyst bed length (cm)	9
Amount of catalysts used (g)	18

solid-tube furnace (Fisher Scientific, Pittsburgh, PA). The furnace is equipped with a single set-point temperature controller for up to a maximum working temperature of 1200 °C. The catalyst bed was placed in the center of the tube and horizontally supported by two alumina foam blocks (MTI Corporation, Richmond, CA). In a typical experiment, syngas flowed into the tube at one end, passed through the catalyst bed, and left at the other end. Residual tar was collected by the tar collection unit.

Table 2 shows the experimental parameters of tar reforming. Temperatures were in the range of 650–850 °C at steps of 50 °C, and NiO loadings ranged from 0% to 20% at steps of 5%. Gas residence times were set at 0.1, 0.3, 0.6, 0.9 and 1.2 s by adjusting the syngas flow rate in the reforming tube through the flow control valve.

2.2.3. Sampling and analysis

The cold trapping method [12] was used for tar collection. The tar sampling system was composed of four 250-ml flasks dipped into an insulation box filled with dry ice as shown in Fig. 1. Each sampling ran for at least 15 min to ensure that more than 100 l of syngas flowed through the cold flasks. All tars and water vapor were collected in the flasks, which were then dried at 105 °C in an oven for 2 h. The residue was considered as tars. Other researchers have used similar or slightly modified forms of this method [37,38]. It must be noted that only heavy tars (boiling point above 105 °C) were measured in this study considering that heavy tars (e.g., heterocyclic compounds, heavy poly-aromatics and asphalt) are more damaging and difficult to remove than lights tars in catalytic cracking.

Syngas was collected from the sampling port or the outlet of the vacuum pump with a 500-ml Tedlar sampling bag. Molar concentrations of H₂, N₂, CO₂, CO, and CH₄ were analyzed with an SRI 8610s gas chromatograph equipped with a thermal conductivity detector (SRI Instruments, Torrance, CA).

3. Results and discussion

3.1. Characterization of Ni catalysts

As shown in Fig. 2, Ni was distributed more uniformly on the surface of the coal char support (Fig. 2b) than on the wood char support (Fig. 2a). This is mainly a result of the porous surface structure of the coal char (Fig. 2d), which enhanced adhesion of NiO particles. The wood char used in this study had relatively smooth and less porous surfaces that did not allow easy deposition of Ni particles.

The elemental compositions of wood char and coal char used in the experiments were analyzed by SEM/EDX. Compared with wood char, coal char contained more O, Na, K, Ca, and Si (Table 3), which are helpful in tar removal [32].

The observation of Ni distributions on chars via SEM/EDX was confirmed by the H₂ chemisorption study. As shown in Table 4, the Ni dispersion rate on the coal char was almost twice as that of on the wood char, and the specific surface area of Ni on the coal char was also significantly bigger than on the wood char, which indicate that the coal char is much better than the wood char as a support for the NiO particles used in this study. In H₂ chemisorption analysis, in addition to the chemical adsorption between H₂ and nickel, physical adsorption of H₂ also occurred on char surfaces when char was used as the catalyst support. However, H₂ adsorbed by char was removed by argon scavenging in the process of catalyst characterization. Therefore, the measured Ni surface areas do not include and were not affected by the surface area of chars.

It must be noted that physical and chemical properties (e.g., porosity and metallic contents) of chars are highly dependent on their origins and production methods [30,39,40]. Consequently, Ni distributions on char support and their tar removal performance are expected to vary with different types of chars. Therefore, observations and analyses above are valid only for the char samples chosen in this study and cannot be generalized to conclude that coal char as a catalyst support is better than wood char, or vice versa.

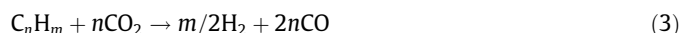
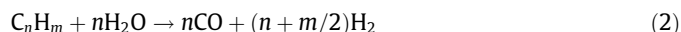
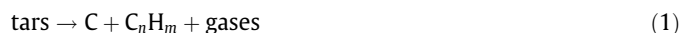
3.2. Catalytic performance of Ni/char catalysts

3.2.1. Effect of reforming temperature

The effect of reforming temperature in the range from 650 °C to 850 °C on tar removal and syngas composition was investigated while NiO loading and gas residence time were fixed at 15 wt.% and 0.3 s, respectively. As shown in Fig. 3, tar removal rate increased with increasing reaction temperature in all cases. Under the same reaction conditions, the Ni/coalchar catalyst showed the highest tar removal rate (ranging from 91% to 99%). Ni/wood-char achieved a slightly lower tar removal rate (86–96%). Without Ni, coal char and wood char could also remove 75–90% tars depending on the temperature. This indicates that char alone is a reasonably effective catalyst for tar removal. Abu El-Rub et al. [30] reported that biomass char decomposed 81% of phenol at 700 °C and more than 94% of naphthalene at 900 °C in a simulated experiment. In another study, Abu El-Rub [32] reported that biomass char removed more than 85% of naphthalene but only 58% of real tars at 750 °C. Gilbert et al. [33] found that the presence of char was helpful, but not to a sufficiently high degree, in promoting heavy tar cracking in a fixed-bed gasifier. Real tars contain heavier and more complicated tars, such as asphaltum, than a model tar. This indicates that char alone is an effective catalyst for light tar removal but lacks sufficient reactivity for heavy tars. Therefore, a Ni catalyst supported by coal char, such as that explored in this study, is a good catalyst design to take advantage of the high reactivity of Ni for heavy tar and effectiveness of char for light tar cracking in syngas cleaning.

Fig. 4 shows concentrations of combustible gases as a function of reaction temperature for the four catalysts. Wood char and coal char slightly enhanced H₂ and CO production compared with no catalyst at all temperatures. Ni/coalchar and Ni/woodchar showed more increases in H₂ and CO, indicating that Ni is more effective than char only in reforming tars to generate CO and H₂.

The following reactions based on the tar thermal cracking and reforming mechanisms proposed by Baker and Mudge [41,42], convert tars and light hydrocarbons into H₂ and CO with the presence of NiO catalysts.



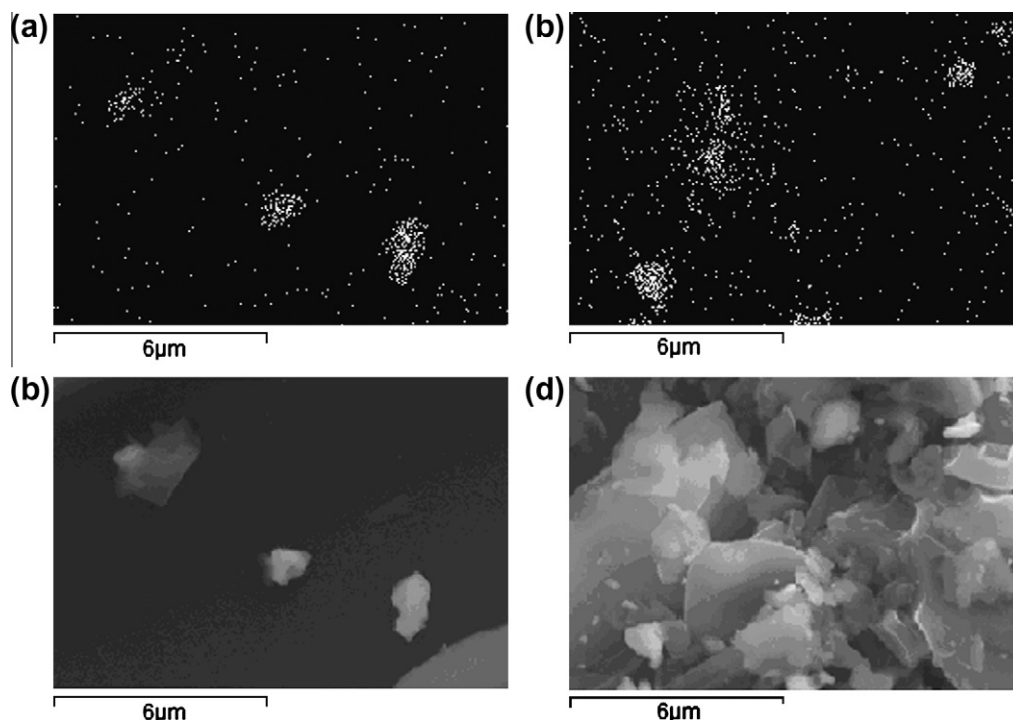


Fig. 2. SEM/EDX images of Ni/woodchar catalyst (a and c) and Ni/coalchar catalyst (b and d) with 15% NiO loading. The bright dots and areas are Ni.

Table 3
Major elements in chars.

Element	Wood char (atomic %)	Coal char (atomic %)
C	91.53	79.06
O	8.03	19.58
Na	–	0.61
Si	–	0.08
K	0.06	0.09
Ca	–	0.56



In addition to the above mechanisms that are common for Ni catalysts, reactions (6) and (7) below may also take place with the presence of char as the catalyst support. Abu El-Rub [32] believed that tars can be adsorbed on the active sites of char particles. The adsorbed tars and cokes formed can be catalytically reformed to CO and H₂ by steam and dry gasification reactions, and meanwhile, free radicals that enter polymerization reactions and coke on char surfaces can be formed from tar decomposition. The gasification reactions of coke cannot only increase CO and H₂ in syngas, but also refresh the active surface area of char at temperature above 800 °C [32]. These reactions may explain the increasing trend of CO vs. temperature because more CO than H₂ is produced.



As expected, H₂ and CO concentrations increased with increasing temperature because of higher reactivity of Ni and char at higher temperatures. These experimental results for Ni/char catalysts agree with findings from other researchers. Le et al. [29] tested the performance of nickel catalysts supported by brown coal char by using the impregnation method in a fluidized bed gasifier; similar to the present study, H₂ and CO concentrations significantly

increased with reaction temperature. However, a temperature above 800 °C may not be worthwhile considering that overheating usually causes sintering of the catalyst and consumes more energy [43]. For this reason, 800 °C was considered an appropriate temperature for tar removal in this study.

3.2.2. Effect of NiO loading

The effect of NiO loading on tar removal and syngas reforming was studied with Ni/woodchar and Ni/coalchar catalysts at 0.3 s

Table 4
Metal dispersion rate, specific surface area of nickel, and diameter of sphere Ni crystallites from H₂ chemisorption analysis of Ni catalysts with 15% NiO loading.

Catalyst	Ni dispersion rate (%)	Diameter of sphere Ni crystallites (nm)	Specific surface area of Ni (m ² /g _{Ni})
Ni/woodchar	25.9	23.7	36.9
Ni/coalchar	46.1	21.7	53.3

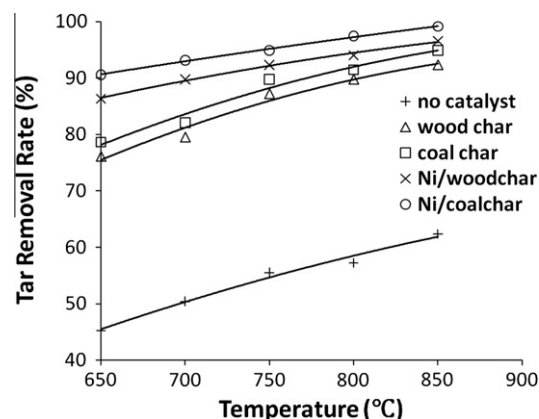


Fig. 3. Effect of catalytic reaction temperature on tar removal. Reaction conditions: 15 wt.% NiO loading when applicable; 0.3 s gas residence time.

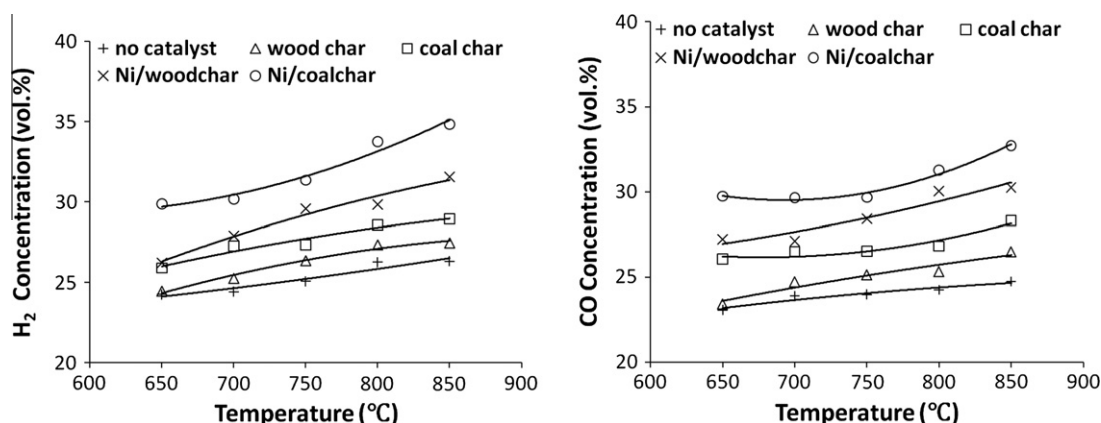


Fig. 4. Effect of catalytic reaction temperature on H₂ (left) and CO (right) concentrations. Reaction conditions: 15 wt.% NiO loading; 0.3 s gas residence time.

gas residence time and 800 °C reaction temperature. As shown in Fig. 5, tar removal rate steadily increased with increasing NiO loading, indicating that Ni plays a significant role in tar removal. The Ni/coalchar catalyst showed better performance than the Ni/woodchar catalyst at all NiO loadings because of the better dispersion of Ni on coal char particles as described in Section 3.1. A rapid increase of tar removal was observed from 10% to 20% NiO loading on wood char, indicating that wood char needs higher loadings of Ni because of poor adhesion of Ni particles on the char surface. This suggests that better mixing of Ni and wood char particles is required. Also, some means to improve adhesion capability and porosity of wood char is needed.

The effect of NiO loading on syngas composition is shown Fig. 6. With the increase of Ni content from 0% to 20%, H₂ concentration significantly increased from 27.33 to 32.53 vol.% for Ni/woodchar and from 28.57 to 34.33 vol.% for Ni/coalchar, which again suggests that it is mainly Ni that enhanced H₂ generation. CO concentration increased only slightly with increasing NiO loading and peaked at 15% NiO loading for both catalysts. When NiO loading further increased from 15% to 20%, CO concentration dropped slightly. These indicate that there is a competition between Ni and char in tar cracking. When Ni is dominant (e.g., at higher NiO loadings or better distribution of Ni on the support surface), more H₂ is generated. On the other hand, more CO is produced if syngas is more exposed to chars than to Ni. Other researchers have observed a similar phenomenon. Bangala et al. [21] reported that syngas yield increased with the loading percentage of Ni on alumina until 15% and

decreased above this percentage. Furusawa and Tsutsumi [19] also reported that when Ni loading on MgO increased from 12% to 36%, the H₂ and CO contents in syngas decreased from 77.2 to 75.9 vol.% and from 2.9 to 2.5 vol.%, respectively. Zhao et al. [20] found that adding more Ni particles did not significantly increase available Ni surface area. Bartholomew and Farrauto [44] explained that nickel dispersion decreased with increasing nickel loading. Therefore, it is not surprising that too much Ni on char deteriorates the performance of the catalyst; 15% could be an optimum NiO loading for the char supports used in this study.

3.2.3. Effect of gas residence time

Fig. 7 shows tar removal rate as a function of gas residence time. Tar removal rate remained high when gas residence time was greater than 0.3 s but decreased significantly below that point. This result indicates that tars need sufficient time (≥ 0.3 s) to decompose, even in the presence of the Ni/coalchar catalyst. When gas residence time increased beyond 0.3 s, the increase of tar removal rate slowed gradually. Longer gas residence times require use of more catalysts or lower syngas flow rates, so a minimal but reasonably effective time is desired. Therefore, 0.3 s was chosen as an appropriate gas residence time to test catalyst performance in other experiments. It is also evident that Ni/coalchar had the best tar removal performance among all catalysts at all gas residence times tested.

Fig. 8 shows the change of H₂ and CO concentrations at various gas residence times. H₂ concentration increased sharply when gas residence time increased from 0.1 s to 0.3 s. After 0.3 s, the increase of H₂ concentration slowed, similar to the trend of tar removal rate. CO concentration also increased with increasing gas residence time and peaked at 0.9 s for the Ni catalysts. Baker and Mudge [11] found that 0.2 s gas residence time was enough to convert more than 90% of phenol at 750 °C. Using a commercial Ni catalyst at 750 °C, Kinoshita et al. [22] found that syngas compositions remained stable after 1.3 s gas residence time. Because tar removal is the main purpose of catalytic reforming, and longer gas residence times require slower syngas flow rates or the use of more catalysts, a minimal but reasonably effective time, such as 0.3 s, is desired.

3.3. Eight-hour performance test

Stability and durability of a catalyst are as important as its reactivity and selectivity. For this reason, the Ni/coalchar catalyst was tested continuously for 8 h in the updraft gasifier. Fig. 9 shows the change of tar removal rate and syngas composition over the testing time at 800 °C, 15 wt.% NiO loading, and 0.3 s gas residence

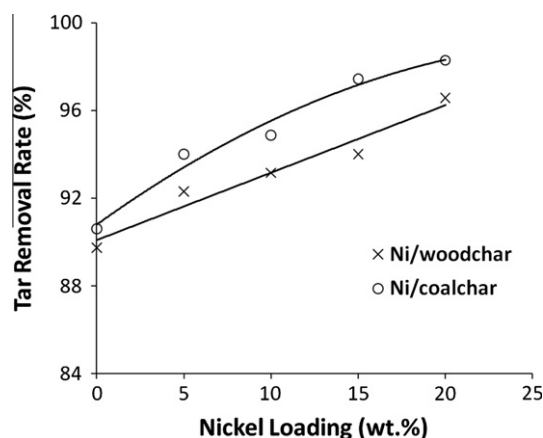


Fig. 5. Effect of NiO loading on tar removal. Reaction conditions: 800 °C reaction temperature; 0.3 s gas residence time.

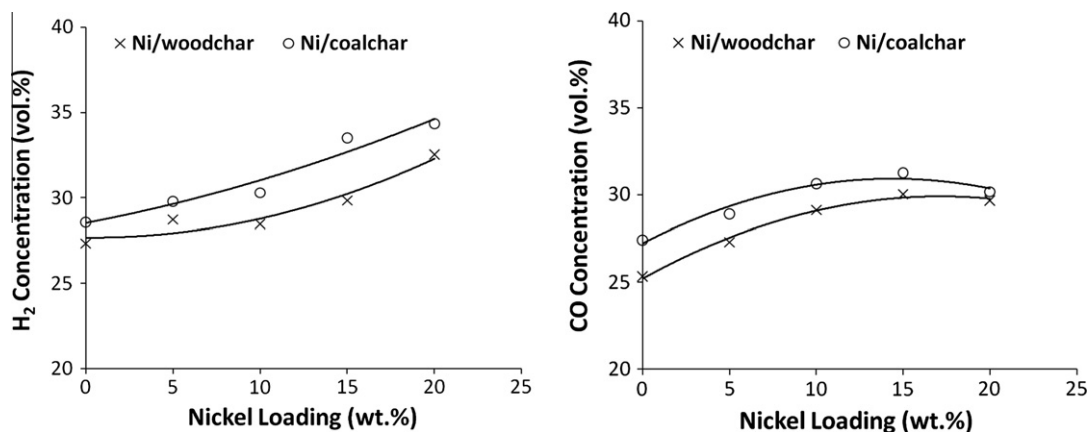


Fig. 6. Effect of catalytic reaction temperature on H_2 (left) and CO (right) concentrations. Reaction conditions: 800 °C reaction temperature; 0.3 s gas residence time.

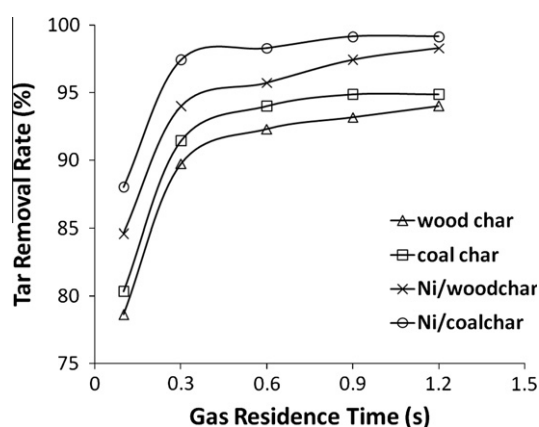


Fig. 7. Effect of gas residence time on tar removal. Reaction conditions: 15 wt.% NiO loading; 800 °C reaction temperature.

time. The Ni/coalchar catalyst exhibited an excellent tar removal rate (>97%) in the first 2 h, and then the rate slightly decreased but remained stable and high after 2 h. CO and H_2 concentrations showed similar trends of a small reduction after 2 h and then stabilized. These phenomena indicate that slight deactivation of the catalyst happened in the early stage of tar/syngas reforming; however, the catalyst was able to stabilize soon after at the selected conditions (800 °C reaction temperature; 15% NiO loading, and 0.3 s gas residence time). A future study should include longer tests

to determine when the catalyst will finally deactivate and how to reduce catalyst deterioration.

The catalyst was weighed before and after the 8-h syngas reforming experiment. Approximately 3.9 g of the 18-g catalyst was lost at the end of the experiment. The cause of catalyst loss is not clear. It may be a result of uncollected catalyst residue on the reforming tube after the experiment, or because of the escape of volatile compounds in chars while heated, or due to the carry-away loss of char particles by syngas flow. It can also be possible that chars were gasified when they are exposed to steam and CO_2 in syngas to generate H_2 and CO as explained in Section 3.2.1. However, the 3.9-g char lost is not enough to generate approximately 490 g increased H_2 and CO, therefore, it is apparent that the increased H_2 and CO in reformed syngas is mainly a result of syngas reforming, but not because of char gasification in the reforming reactor.

Performance of the Ni/coalchar catalyst was similar to that of Ni/ γ - Al_2O_3 in terms of tar removal and syngas reforming [45]. There are several advantages to using chars as the catalyst support. First, chars are less expensive than metal oxides. Second, Ni can be saved by using char as the support. Ni particles stay only on the outer surface of the char support. In metal-oxide-supported catalysts, however, Ni is also formed inside the support via the impregnating and calcining methods. The outer surfaces of catalysts are active sites, but the inside of the support is usually not; thus, a fraction of Ni is not in effective in the Ni/ γ - Al_2O_3 catalyst. Third, mechanical mixing of Ni and char saves energy and time in catalyst preparation. The multistep impregnating method is very time consuming. A few hours are required for the Ni precursor to penetrate

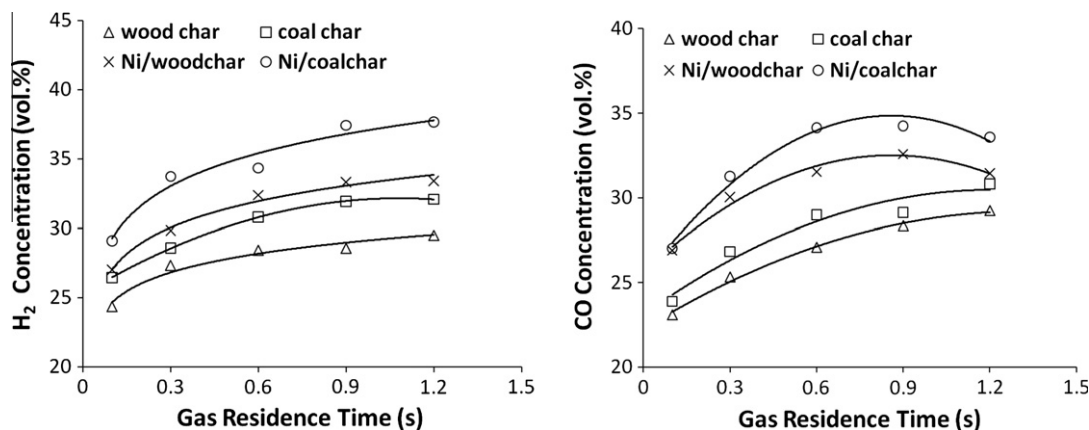


Fig. 8. Effect of gas residence time on H_2 (left) and CO (right) concentrations. Reaction conditions: 15 wt.% NiO loading; 0.3 s gas residence time.

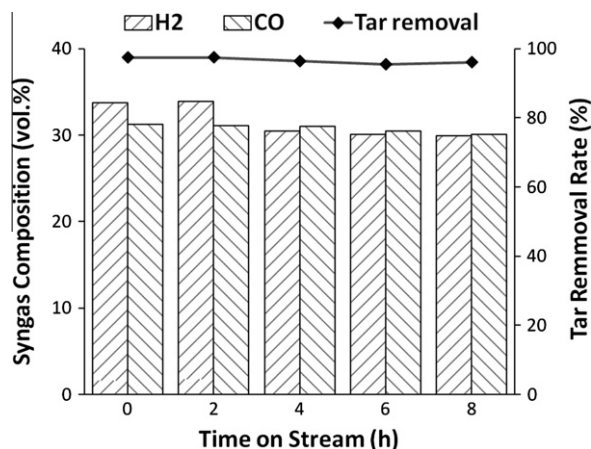


Fig. 9. Effect of time on stream on syngas composition and tar removal for the NiO/coalchar catalyst. Reaction conditions: 15 wt.% NiO loading; 800 °C reaction temperature; 0.3 s gas residence time.

into the support, a few additional hours are needed for drying, and then the process is repeated. The calcining process is also time and energy consuming. Mechanically mixing Ni and char to prepare the catalyst is much faster and more energy efficient.

4. Conclusion

Wood and coal chars were used as the catalyst support of Ni. Char and NiO particles were mechanically mixed at various ratios and studied for tar removal in a laboratory-scale updraft biomass gasifier. A reaction temperature of 800 °C, NiO loading of 15 wt.%, and gas residence time of 0.3 s were deemed appropriate. The Ni/coalchar and Ni/woodchar catalysts removed more than 97% of tars in syngas at the optimum reforming conditions. Analysis of syngas compositions indicated that concentrations of H₂ and CO in syngas significantly increased because of Ni/char catalytic cracking/reforming of tars. The catalytic performance of catalysts in this study was ordered as Ni/coalchar > Ni/woodchar > coal char > wood char > no catalyst. Furthermore, performance of the Ni/coalchar catalyst was tested for 8 h. There was a slight deactivation of the catalyst in the early stage of tar/syngas reforming; however, the catalyst was able to stabilize soon after. Using char as the Ni catalyst support has several advantages over metal oxides, such as being more economical, reducing use of Ni in reforming, and saving energy and time in catalyst preparation. Based on the results from this study, it is evident that chars especially coal char can be an effective support of Ni for biomass gasification tar removal and syngas conditioning.

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