Preparation of a Ni/LaAlO$_3$ Catalyst and its Application in Catalytic Pyrolysis of Soybean Straw for Syngas Production

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A LaAlO$_3$ carrier was prepared via the sol-gel method, and a Ni/LaAlO$_3$ catalyst was prepared via the homogeneous precipitation method; this catalyst was used for the catalytic pyrolysis of soybean straw for syngas (H$_2$ + CO) production. The analysis of the raw materials (straw) was performed via elemental analysis and industrial analysis. The support and catalyst were characterized and analyzed by X-ray fluorescence spectroscopy, thermogravimetric analysis, X-ray diffraction, scanning electron microscopy, and N$_2$ adsorption-desorption isotherms. The results illustrated that the NiO was uniformly loaded on the LaAlO$_3$ surface. Furthermore, the effects of the Ni loading amount, pyrolysis temperature, holding time, and calcination temperature on the performance of the catalyst were studied. The results showed that the catalyst had the highest increase in production and concentration of H$_2$ and CO when the Ni loading was 10 wt%, the calcination temperature was 500 °C, the reaction temperature was 800 °C, and the holding time was 20 min. Compared with the pyrolysis of straw without a catalyst, the yield of H$_2$ and CO increased from 85 mL/g and 125 mL/g to 238.5 mL/g and 255 mL/g, respectively, and the concentration of H$_2$ and CO increased from 23.5 vol% and 29.4 vol% to 43.1 vol% and 41.9 vol%, respectively.

Keywords: LaAlO$_3$; Catalytic pyrolysis; Soybean straw; Syngas

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INTRODUCTION

With the continued development of society and the economy, energy and environmental issues have become increasingly prominent, especially the increase in energy consumption, which is led by fossil energy. The development and consumption of fossil energy will eventually become unsustainable (Saxena et al. 2009). Biomass is a renewable raw material that can be produced with straw (among other materials), which can be converted into solid, liquid, and gas fuels through chemical and biological processes (Zhao and Yan 2012). Pyrolysis is one of the most effective technologies for converting biomass into fuel. The products are gas, tar, and coke. However, the yield of syngas produced via the pyrolysis of straw in the absence of a catalyst is low, the combustible gas content is low, the calorific value is low, and a large amount of tar is generated. The tar in the gas is easily condensed at low temperatures, and it has a long accumulation time, which leads to pipe blockages and other problems (Hossain et al. 2016). Moreover, it will cause energy loss and environmental problems related to tar.

However, the formation of toxic and harmful organic compounds can be avoided. Increased attention has been paid to catalytic reforming technology, which can convert
biomass, i.e., straw, into syngas with almost no tar at a lower temperature (Li et al. 2013). Nickel-based catalysts are widely used for gasification, tar conversion, and the reformation of light hydrocarbons due to their high tar destructive activity and ability to increase the content of syngas in the produced gas (Li et al. 2009; Li et al. 2014; Gao et al. 2017).

Commonly used nickel-based catalyst supports are divided into metal oxides (Al₂O₃, MgO, etc.), natural ores (dolomite, olivine, and palygorskite), and natural zeolite molecular sieves (Xu et al. 2013; Zou et al. 2017; Lian et al. 2018; Tan et al. 2019; Li et al. 2020). Li et al. (2013) prepared a NiO/γ-Al₂O₃ catalyst for the steam reforming of rice biomass, and they compared the performance of SiO₂, CaO, and TiO₂ as a support catalyst. The results showed that γ-Al₂O₃ had better performance, better tar catalytic cracking ability, and drastically improved hydrogen production. However, a catalyst based on an alumina support did not yield positive results in terms of coke deposition, due to its strong acidity. Wei et al. (2018) synthesized mesoporous Ni-Mg-Al and Ni-Al catalysts and used them in the dry reformation of methane and the coupling reformation of a partial oxidation reaction of methane. The results showed that compared to Ni-Al and Ni/Al₂O₃ catalysts, Ni-Mg-Al catalysts had a larger surface area, higher Ni dispersion, smaller Ni particle size, higher gas (H₂ + CO) synthesis, and excellent stability. Loy et al. (2018) found that compared with the commercial catalysts (nickel and natural zeolite) in rice husk catalytic pyrolysis, using coal bottom ash catalyst can generate higher syngas content and lower coke formation. Chein and Fung (2019) studied the application of CeO₂ modified Ni/Al₂O₃ catalyst in dry reforming of methane to syngas. It was found that CeO₂ promoted the reaction of DMR. When O₂ was added to the reaction, the carbon deposition of CeO₂ modified Ni/Al₂O₃ catalyst was the lowest. Claude et al. (2019) studied the properties of Ni/γ-Al₂O₃ catalyst prepared by the sol-gel method and the wet impregnation method. It was found that the catalyst prepared by the sol-gel method had more stable catalytic activity and lower carbon deposition. Zhao et al. (2019) used NiAl-LDHs/FeCrAl fiber as the catalyst precursor and prepared Ni-CeAlO₃-Al₂O₃/FeCrAl fiber flakes for COMR process by thermal delamination, CeO₂-modification, and H₂-reduction. The use of a “CeAlO₃-CeO₂” cycle enables the catalyst with high carbon resistance because of the intensified C-elimination to inhibit filaments growth. Perovskite composite oxides have unique crystal structures, especially the crystal defect structure and the properties formed after doping, which has multiple applications as a replacement to precious metals, such as its usage as or in solid fuel cells, solid electrolytes, sensors, high temperature heating materials, solid resistors, and oxidation-reduction catalysts. As such, this material has become a research hotspot in the fields of chemistry, physics, and materials. Figueredo et al. (2018) studied and compared the use of perovskite LaAlO₃ and commercial α-Al₂O₃ supported nickel catalyst in the dry reformation of methane. It was found that perovskite type LaAlO₃ had a more stable performance than Al₂O₃, and the LaAlO₃ was prepared via a microwave assisted thermal method. However, the preparation of LaAlO₃ as a catalyst carrier by sol-gel method has rarely been reported. La as a metal carrier can improve the activity of nickel catalyst and prevent sintering. The amount of La is small and the cost increases slightly. Therefore, the LaAlO₃ carrier was prepared by sol-gel method, and then Ni/LaAlO₃ accelerator was prepared by homogeneous precipitation method. The raw materials were characterized by elemental analysis, XRF, XRD, SEM, and BET. The pyrolysis experiments of soybean straw were carried out. The effects of nickel loading, reaction temperature, holding time and calcination temperature of the catalyst on the performance and stability of the catalyst were investigated.

EXPERIMENTAL

Materials
Soybean straw (SS), which was collected in Lvliang, Shanxi province, China, was chosen as the biomass feedstock in this study. Prior to testing, the soybean straw was crushed and sieved to obtain particles that were size 60 mesh and lower. The straw was then dried at 105 °C for 24 h, and then sealed in the drying oven to eliminate the introduction of additional moisture content. The ultimate and proximate analysis of the soybean straw samples (as shown in Table 1) were both conducted using an elemental analyzer (Flash 2000, Thermo Fisher Scientific, Waltham, MA) and according to GB/T standard 28731 (2012).

<table>
<thead>
<tr>
<th>Table 1. Proximate and Ultimate Analyses of the Soybean Straw</th>
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<tbody>
<tr>
<td><strong>Materials</strong></td>
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<tr>
<td></td>
</tr>
<tr>
<td>Soybean Straw</td>
</tr>
</tbody>
</table>
* by difference; M: Moisture; V: Volatile matter; A: Ash; FC: Fixed Carbon

Preparation of support and catalyst
All reagents used were purchased from Aladdin industries (Shanghai, China).
LaAlO$_3$ was prepared via the sol-gel method. 4.6g La(NO$_3$)$_3$·6H$_2$O and 9.6g citric acid were mixed and dissolved in deionized water, and 5.4g Al(NO$_3$)$_3$·9H$_2$O was dissolved in deionized water and stirred, making it completely dissolved. Then it was poured into a lanthanum nitrate citric acid mixture, stirred vigorously for 1 h, then evaporated into a gel. The material was put in a 200 °C oven to dry overnight, and then it was placed in a 800 °C muffle furnace for calcination.
Ni/LaAlO$_3$ catalyst was prepared via the homogeneous precipitation method with Ni(NO$_3$)$_2$·6H$_2$O as the nickel precursor and LaAlO$_3$ as the support. First, 5 g of LaAlO$_3$ was placed in a 500 mL three neck flask, and then Ni(NO$_3$)$_2$·6H$_2$O and CON$_2$H$_4$ (in a mass ratio of 1:4) were mixed with 100 mL of deionized water.
After the mixture was completely dissolved, it was poured into a three-neck flask, stirred in an oil bath at 115 °C for 2 h, and aged for 2 h. Next, the mixture was filtered and washed. It was then dried at 105 °C for 12 h. The dried catalyst precursor was calcined in a muffle furnace at a set temperature for 2 h to obtain the catalyst (NiO/LaAlO$_3$). The catalysts were prepared with different parameters, as follows: a Ni loading amount of 5 wt%, 10 wt%, 15 wt%, or 20 wt% and a calcination temperature of 500 °C, 600 °C, 700 °C, or 800 °C.

Instruments and Experimental Methods
The experimental device is shown in Fig. 1, which included a gas supply system, pyrolysis reactor, gas purification device, gas collection bag, and analysis system. The tests were conducted in a horizontal fixed-bed quartz tube reactor. The furnace was on the top of the tube reactor and surrounded the quartz tube to ensure that it was heated. Two quartz boats were each used to separately hold the biomass and catalyst, with an inner diameter of 40 mm, a length of 100 mm, and a height of 10 mm.
The gas purification device was placed in an ice water bath to completely eliminate the influence of tar. The reactor had an inner diameter of approximately 60 mm, had a total length of 1400 mm, and had a flat-temperature zone of 600 mm.

First, 2 g of straw and 0.5 g of catalyst were put into two quartz boats in the reactor, and then the flanges on both sides were closed. Nitrogen at a flow rate of 100 mL/min was continuously introduced into the entire system for 30 min under room temperature to ensure an oxygen-free environment. Subsequently, the reactor temperature was increased from room temperature to the specified temperature (600 °C, 700 °C, 800 °C, or 900 °C) at a heating rate of 10 °C/min and maintained for a specified time (5 min to 30 min). When the flat-temperature zone was preheated to the target temperature, the two boats were quickly pushed to the furnace. After the reaction time reached the set time, the furnace was pushed away and the valves on both sides of the tube were opened. Meanwhile, the syngas was collected in the gas sample bag. Finally, the gas composition and content of the syngas were determined via the gas analyzer. Each group of tests was repeated three times to take the average value to ensure the reliability of the collected data.

**Methods**

The elemental composition and material structure of the catalysts were analyzed via X-ray fluorescence spectrometer (EDX-7000, SHIMADZU, Kyoto, Japan) and X-ray diffraction (XRD-7000, SHIMADZU, Kyoto, Japan). A thermogravimetric analyzer (SDT Q600, TA Instruments, New Castle, DE) was used to evaluate the thermal stability of the support, catalyst, and used catalyst. The specific surface area and pore structure of the support, catalyst, and used catalyst were measured via a surface area analyzer (ASAP 2020 HD88, Micromeritics, Norcross, GA). The microstructure of the support, catalyst, and used catalyst were analyzed via scanning electron microscopy (S-3000N SEM, HITACHI, Tokyo, Japan). The volatile gas was collected with a gas sample bag and analyzed via an infrared gas analyzer (Gasboard-3100, Cubic-Ruiyi, Wuhan, China). Considering that the relative content of CH4 and other hydrocarbons (CnHm) could be neglected, this experiment only evaluated the performance of the catalysts by measuring the synthesis gas content (H2 + CO).
RESULTS AND DISCUSSION

Characterization of the Ni/LaAlO₃ Catalyst

X-ray fluorescence analysis

The elemental compositions of the LaAlO₃ and Ni/LaAlO₃ catalysts are shown in Table 2. The XRF analysis showed that the main components of the support were La and Al. The support was calcined in air to form LaAlO₃. After the nickel was loaded, it oxidized into NiO after being calcined by a muffle furnace. The loading amount of NiO in the catalyst was consistent with the theoretical loading amount.

Table 2. XRF Analyses of the LaAlO₃ and Ni/LaAlO₃ Catalyst

<table>
<thead>
<tr>
<th>Sample</th>
<th>Main Composition and Content (wt%)</th>
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<tbody>
<tr>
<td></td>
<td>La₂O₃</td>
</tr>
<tr>
<td>LaAlO₃</td>
<td>77.78</td>
</tr>
<tr>
<td>Ni/LaAlO₃</td>
<td>70.75</td>
</tr>
</tbody>
</table>

X-ray diffraction analysis

Figure 2 shows the XRD spectra of the LaAlO₃ and Ni/LaAlO₃ catalysts. There were some characteristic peaks at 2θ at values of 23.3°, 33.5°, 41.2°, 47.9°, 54.0°, 59.6°, 70.1°, 75.0°, 79.9°, and 84.6°, which could be identified as the characteristic peaks of LaAlO₃ (PDF # 70-4108). The peaks at 27.7°, 43.3°, and 63.9° were identified as characteristic NiO peaks (PDF # 78-0429), which indicated that NiO/LaAlO₃ was formed after the catalyst was calcined. Therefore, it was concluded that the Ni existed in the form of NiO, which coincided with the XRF analysis. The peaks at 44.4° and 51.7° were identified as the characteristic peaks of Ni (PDF # 89-7128), and the active component changed from NiO to elemental Ni.

![XRD patterns of LaAlO₃ and Ni/LaAlO₃ catalysts](image)

Hu et al. (2018) showed that the conversion of NiO to Ni through hydrogenation reduction could help improve tar conversion rates. The peak at 44.3° was identified as the characteristic peak of C (PDF # 80-0017), which indicated a small amount of carbon.
deposits on the catalyst surface. Due to the formation of these carbon deposits, the catalyst pore structure would become blocked, such that the active sites of the catalyst were covered. Therefore, the catalyst activity would decrease after being used.

**Thermogravimetric analyzer**

The thermogravimetric curves of LaAlO₃ and Ni/LaAlO₃ are shown in Fig. 3. As shown, the TG curves of the carrier and the catalyst were almost straight lines, which indicated that the carrier and the catalyst had good thermal stability. This high thermal stability provided good support for subsequent experiments.

![Fig. 3. Thermogravimetric analyzer of LaAlO₃ and Ni/LaAlO₃](image)

**Temperature program reduction (TPR)**

According to the TPR-H₂ curve (Fig. 4), the reduction temperature of Ni/ LaAlO₃ catalyst is between 249 and 478 °C, but there are two shoulders between 95 and 241 °C.

![Fig. 4. TPR analysis results for LaAlO₃ and Ni/LaAlO₃](image)
This may be attributed to the easy removal of \( \text{O}^{2--} \) ions from \( \text{NiO/LaAlO}_3 \) interface. This is the particularity of \( \text{Ni/LaAlO}_3 \) catalyst, because the pure \( \text{LaAlO}_3 \) carrier does not show the reduction curve (Fig. 4). Although the contribution of these two events to the reduction curve of \( \text{Ni/LaAlO}_3 \) is very small, their role in catalyst activation may be very important due to the vacancy on the \( \text{NiO/support} \) interface.

**Scanning electron microscope analysis**

The surface morphology of the \( \text{LaAlO}_3 \) support, \( \text{Ni/LaAlO}_3 \) catalyst, and used \( \text{Ni/LaAlO}_3 \) catalyst are presented in Fig. 5. The support had a mesoporous structure, as shown in Fig. 5a, which could allow for \( \text{NiO} \) to be uniformly loaded on the surface of the support, as shown in Fig. 5b. This was consistent with the BET analysis results, and it effectively increased the active surface area and provided more contact parts for tar cracking in the gas. Figure 5c showed that the used \( \text{Ni/LaAlO}_3 \) catalyst particles had agglomerated, the particle size was not uniform, and it was covered with carbon, which resulted in decreased catalyst activity (Xiao et al. 2013).

![Fig. 5. SEM images of (a) \( \text{LaAlO}_3 \), (b) \( \text{Ni/LaAlO}_3 \), and (c) used \( \text{Ni/LaAlO}_3 \)](image)

**Analysis of specific surface area and pore structure**

The \( \text{LaAlO}_3 \), \( \text{Ni/LaAlO}_3 \), and used \( \text{Ni/LaAlO}_3 \) \( \text{N}_2 \) adsorption-desorption isotherms, as well as the BJH pore size distributions, are shown in Fig. 6, and the related parameters are shown in Table 3. The \( \text{N}_2 \) adsorption-desorption isotherms of the three samples had obvious hysteresis loops. According to IUPAC classification, all the isotherms conformed to the IV model. The pore sizes of the \( \text{LaAlO}_3 \) support and \( \text{Ni/LaAlO}_3 \) catalyst were mainly distributed between a range of 50 nm to 250 nm, and the pore sizes of the used \( \text{Ni/LaAlO}_3 \) catalyst were mainly distributed within a range of 50 nm to 175 nm. This further indicated that the three samples had a mesoporous structure. The mesoporous structure of the catalyst was conducive to the further adsorption of tar, which promoted full contact between the tar and the active components, which led to additional cracking, i.e., an increase in syngas production. According to Table 3, the BET surface areas of the \( \text{LaAlO}_3 \) support, the \( \text{Ni/LaAlO}_3 \) catalyst, and the used \( \text{Ni/LaAlO}_3 \) catalyst were 12.63, 22.11, and 14.52 \( \text{m}^2\cdot\text{g}^{-1} \), respectively. In addition, it was shown that the specific surface area and pore volume of the Ni-supported catalyst was increased when compared to the \( \text{LaAlO}_3 \) support. However, the pore diameter decreased, which suggested that the addition of Ni to the \( \text{LaAlO}_3 \) structure increased the level of Ni dispersion (Lim et al. 2007). The Ni in the perovskite catalyst could become more reducible than the \( \text{LaAlO}_3 \), which would lead to the formation of small particle on the surface and more abundant dispersion (Lim et al. 2009). The decrease in specific surface area and pore volume of the used \( \text{Ni/LaAlO}_3 \) was due to a small amount of carbon deposits on the catalyst surface after the reaction, which was consistent with the SEM analysis results.
Table 3. Textural Parameters of LaAlO\textsubscript{3}, Ni/LaAlO\textsubscript{3}, and Used Ni/LaAlO\textsubscript{3}

<table>
<thead>
<tr>
<th>Sample</th>
<th>LaAlO\textsubscript{3}</th>
<th>Ni/LaAlO\textsubscript{3}</th>
<th>Used Ni/LaAlO\textsubscript{3}</th>
</tr>
</thead>
<tbody>
<tr>
<td>BET Surface Area (m\textsuperscript{2}\cdot g\textsuperscript{-1})</td>
<td>12.6309</td>
<td>22.1070</td>
<td>14.5179</td>
</tr>
<tr>
<td>Total Pore Volume (cm\textsuperscript{3}\cdot g\textsuperscript{-1})</td>
<td>0.097950</td>
<td>0.165453</td>
<td>0.115160</td>
</tr>
<tr>
<td>Average Pore Diameter (d/\text{nm})</td>
<td>110.434</td>
<td>109.872</td>
<td>121.142</td>
</tr>
</tbody>
</table>

Fig. 6. The N\textsubscript{2} adsorption-desorption isotherm plots and BJH cumulative pore distribution of various catalysts: (a) LaAlO\textsubscript{3}, (b) Ni/LaAlO\textsubscript{3}, and (c) Used Ni/LaAlO
Application and Performance of Ni/LaAlO$_3$ Catalyst in Straw Fueled Pyrolysis

Effect of nickel load and reaction temperature on syngas production

Figure 7 shows the effect of the total amount of nickel load (from 5 wt% to 20 wt%) on syngas production at different reaction temperatures. During this test, the calcination temperature and holding time were fixed at 500 °C and 20 min, respectively. The yield of syngas produced via straw fueled pyrolysis was different as the total amount of nickel loaded was changed. When the nickel loading amount was 10 wt%, the H$_2$ and CO yield were the highest, and it was shown that when the reaction temperature increased, the H$_2$ and CO yield also gradually increased. These results were all based on the experiment with a 10 wt% nickel loaded catalyst.

![Figure 7. Effect of Ni load and reaction temperature on the yield of syngas (a) H$_2$ and (b) CO](image)

Effect of the reaction temperature

The effect of the reaction temperature (ranging from 600 °C to 900 °C) on the syngas concentration was studied with a total Ni loading amount of 10 wt%, a calcination temperature of 500 °C, and a holding time of 20 min. The dependence of the H$_2$ and CO concentration on the reaction temperature is depicted in Fig. 8, which conveyed that the gas concentration increased as the reaction temperature was increased when the SS was pyrolyzed without a catalyst. As the temperature was increased along the range of 600 °C to 900 °C, the H$_2$ and CO concentration experienced an upward trend, increasing from 16.86 vol% to 33.87 vol% and 18.05 vol% to 35.57 vol%, respectively. When the catalyst was added, the synthesis gas concentration drastically changed. As shown in Fig. 8, at the same reaction temperature, the concentration of H$_2$ and CO after the pyrolysis of SS with a Ni/LaAlO$_3$ catalyst was always higher than the concentration without catalyst. After using the catalyst, the H$_2$ and CO concentrations increased from 35.33 vol% and 26.98 vol% to 43.5 vol% and 42.67 vol%, respectively. However, as shown in Fig. 8, when the pyrolysis temperature rose from 800 °C to 900 °C, the H$_2$ and CO content increased from 43.1 vol% and 41.9 vol% to 43.5 vol% and 42.67 vol%, respectively. At 800 °C, the concentration of H$_2$ and CO increased from 23.5 vol% and 29.4 vol% to 43.1 vol% and 41.9 vol%, respectively, which was relatively low when compared to the increase in H$_2$ and CO content without a Ni/LaAlO$_3$ catalyst. As shown in Fig. 7, the production of H$_2$ and CO increased from 85 mL/g and 125 mL/g to 238.5 mL/g and 255 L/g, respectively, so the optimal pyrolysis temperature was 800 °C.
Effect of the holding time

The effect of the holding time (ranging from 5 min to 30 min) on the syngas concentration was studied with a total Ni loading amount of 10 wt%, a reaction temperature of 800 °C, and a calcination temperature of 500 °C. The dependence of the H₂ and CO concentration on the holding time is depicted in Fig. 9. As the holding time increased, the H₂ and CO concentrations also increased, but when the holding time exceeded 20 min, the concentration continued to only slightly increase; therefore, a holding time of 20 min was chosen. Compared with no catalyst at the same time, the addition of the Ni/LaAlO₃ catalyst, the H₂ and CO concentrations increased from 23.5 wt% and 29.4 wt% to 43.1 wt% and 41.9 wt%, respectively.
Effect of the calcination temperature

The effects of calcination temperature (ranging from 500 °C and 800 °C) on the syngas concentration was studied with a nickel loading, reaction temperature, and holding time of 10 wt%, 800 °C, and 20 min, respectively. Figure 10 shows the change in syngas concentration as the calcination temperature of the catalyst was increased. At a calcination temperature of 500 °C, the concentration of H₂ and CO reached its peak value of 43.1 wt% and 41.9 wt%, and the syngas concentration was 85 wt%. As the calcination temperature increased from 500 °C to 800 °C, the syngas concentration decreased from 85 wt% to 78 wt%, which indicated that the high calcination temperature decreased the catalyst activity.

![Fig. 10. Effect of the calcination temperature on the syngas concentration](image)

Effect of the reuse times

The reuse times were obtained by cooling the catalyst to room temperature after doing one set of experiments and then conducting the next set of experiments. The effect of repeated usage of a Ni/LaAlO₃ catalyst on the catalytic effect was studied. As shown in Fig. 11, as the number of uses increased, the concentration of H₂ and CO decreased.
Fig. 11. Effect of the reuse times on the syngas concentration: (a) H₂ and (b) CO

Although the concentration of H₂ and CO decreased slightly in the first four experiments, they all exceeded 35 wt%. When used a fifth time, the concentration of H₂ and CO sharply decreased. During the sixth and seventh experiment, the concentration of H₂ and CO was nearly the same as that the concentrations recorded without a catalyst. This was attributed to the fact that more carbon deposits covered the active sites on the surface of the catalyst as the number of the use times increased, which led to lower catalytic activity of the catalyst (Qian and Kumar 2017).

CONCLUSIONS

1. The carrier prepared via the sol-gel method has good thermal stability. The nickel was uniformly loaded on the LaAlO₃ carrier via homogeneous precipitation, and the NiO uniformly dispersed on the surface of the carrier.

2. As the catalyst calcination temperature was increased from 500 °C to 800 °C, the synthesis gas concentration showed a downward trend.

3. The best performance with the usage of a Ni/LaAlO₃ catalyst for syngas preparation was obtained under the following conditions: a Ni loading amount of 10 wt%, a calcination temperature of 500 °C, a reaction temperature of 800 °C, and a holding time of 20 min.

4. When the reaction temperature was increased from 800 °C to 900 °C, although the synthesis gas concentration increased, the increase was not very obvious. The concentration of H₂ and CO increased from 43.1 wt% and 41.9 wt% at 800 °C to 43.5 wt% and 42.67 wt% at 900 °C, respectively.

5. A Ni/LaAlO₃ catalyst has good stability and can be reused 4 to 5 times.
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