Upgrading biomass fuel gas by reforming over Ni–MgO/γ-Al2O3 cordierite monolithic catalysts in the lab-scale reactor and pilot-scale multi-tube reformer

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The effect of Ni/Mg mole ratio of Ni–MgO/γ-Al2O3 cordierite monolithic catalysts on dry reforming of model biomass fuel gas (H2/CO/C2H4/CH4/CO2/N2 = 16.0/12.1/2.5/15.1/22.0/32.3, vol.%) was investigated in a lab-scale stainless steel tubular reactor. The results showed that CH4 and CO2 conversions, H2 and CO yields and H2/CO ratio in the tail gas was 87.2%, 54.4%, 65.2%, 43.0%, and 1.17 respectively at 750°C over the optimized MCNi0.51Mg0.49O (the ratio was 0.51:0.49 with 8.3 wt% NiO loading amount) during 60 h of time on stream (TOS). And the formation of NiO–MgO solid solution structure would restrain the active Ni0 centers from agglomeration and decrease carbon deposition. Cold test of the vertical-placed tubular reformers (packed by monolith of 7 mm cell spacing) indicated that the pressure drop was as low as 850 Pa at 1.57 m/s of gas velocity with 330 g/m3 fly ash added. The reforming of real biomass fuel gas (H2/CO/C2H4/CH4/CO2/N2 = 10.2/16.8/0.5/6.4/15.2/51.0, vol.%, from air gasification of 200–250 kg/h pine sawdust in the pilot plant) in the multi-tube reformer packed with MCP (larger in size than MCNi0.51Mg0.49O) exhibits the pressure drop of less than 700 Pa, CH4 and CO2 conversions of about 84% and 38.5% and the decrease of tar content from 4.8–5.3 g/m3 to 0.12–0.14 g/m3 during 60 h TOS at 670°C. The characterization of the spent catalysts by TG, XRD and ICP-AES proved the anti-sintering and anti-carbon deposition properties of NiO–MgO solid solution monolithic catalyst.

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1. Introduction

Thermo-chemical gasification of biomass is inevitably accompanied by the formation of tar [1] and the obtained raw fuel gas is usually CO2-rich with low H2/CO ratio [2]. Reforming of CH4, tar and other light hydrocarbons with CO2 to increase H2/CO ratio and upgrading raw biomass fuel gas have been carried out extensively in the past decades [3]. Although Ni-based catalysts showed high efficiency in reforming reaction, their rapid deactivation by carbon deposition and active Ni0 particle sintering were obvious [4,5]. Recently using cordierite monolith as support has attracted much attention [6,7]. Ru, Pt and Ni-based monolithic catalysts were reported [8,9]. The advantages of monolithic catalyst-packed reactor are notable: good mass transfer performance, high operating stability, low-pressure drop, and easy separation of products [10,11].

Preliminary results from our group showed that NiO–MgO solid solution powdery catalyst achieved high activity for reforming raw biomass fuel gas from air–steam gasification [12]. Ni/γ-Al2O3 monolithic catalyst also exhibited remarkable CH4 and tar conversion during model biomass fuel gas reforming [13].

In the present work, dry CO2 reforming of model biomass fuel gas with naphthalene adding as model tar component over Ni–MgO/γ-Al2O3 cordierite monolithic catalysts (MCNiMgO with different Ni/Mg mole ratio) was evaluated in lab-scale stainless steel tubular reactor. And the application of the optimized catalyst for reforming of real raw biomass fuel gas, derived from fluidized-bed air gasification of pine sawdust (200–250 kg/h) was also discussed in a multi-tube reformer. The design and operation condition of the reformer were preliminarily discussed to obtain useful information for the design of large-scale biomass to liquid fuel projects (BTL). In the same time the spent catalysts were characterized by TG, XRD and ICP-AES to probe the anti-sintering and anti-carbon deposition properties of the NiO–MgO solid solution structure.

2. Experimental section

2.1. Catalyst preparation

Two types of ceramic cordierite monolithic substrate (Yixing Nonmetallic Chemical Factory, China) with the density, porosity,
BET, cell density, cell spacing, specification of 1.71 g/cm$^3$, 60%, 10.9 m$^2$/g, 60 cells/cm$^2$, 1 mm, φ4.0 × 5.0 cm and 1.03 g/cm$^3$, 90%, 10.4 m$^2$/g, 15 cells/cm$^2$, 7 mm, φ9.0 × 10.0 cm were used to prepare catalysts for reforming model and real biomass fuel gas respectively. At first, the bare monoliths were immersed into 30 wt% oxalic acid solution for 0.5 h, dipped into the ethanol suspension of ultrafine γ-Al$_2$O$_3$ powder under vacuum condition to increase pore volume and surface area. Then γ-Al$_2$O$_3$-coated monoliths were impregnated by 1 N aqueous magnesium nitrate solutions, dried overnight at 110°C and calcined at 900°C. After that, MgO-loaded monolith was impregnated again by 1 N aqueous nickel nitrate solutions, dried overnight at 110°C and calcined at 850°C. These two types of well-prepared catalysts were denoted as MCNi$_{0.51}$Mg$_{0.49}$O and MCP, respectively.

The other two MCNiMgO catalysts of MCNi$_{0.40}$Mg$_{0.60}$O and MCNi$_{0.62}$Mg$_{0.38}$O were also prepared with different Ni/Mg mole ratios to compare the reforming performance with MCNi$_{0.51}$Mg$_{0.49}$O. The chemical compositions of MCNiMgO catalysts are listed in Table 1. The uniform nickel distribution along the axial direction was visually examined by cutting the monolith substrate was visually examined by cutting the monolith lengthwise into two semi-cylinders [14].

### 2.2. Dry reforming of model biomass fuel gas in lab-scale test

Lab-scale dry reforming of model biomass fuel gas (H$_2$/CO/C$_2$H$_4$/N$_2$, 16.0/12.1/2.5/15.1/22.0/32.3, vol%) was carried out in a stainless steel tubular reactor (45 mm I.D., horizontal-placed), packed with one piece of MCNiMgO catalyst, at atmospheric pressure and 300 mL/min of gas flow rate. Naphthalene was carried to the reactor as model tar component in raw biomass fuel gas [15]. Naphthalene content was strictly controlled by water bath heating. Before each run, MCNiMgO was reduced in situ at 850°C in 300 mL/min of 5% H$_2$/N$_2$ (vol) flow for 2 h, and then exposed to model biomass fuel gas and naphthalene. The tail gas passed through water absorber, sampled into gas bag for off-line GC and GC–MS analysis. CO, N$_2$, CH$_4$ and CO$_2$ were analyzed by carbon-sieve column with TCD detector; gaseous hydrocarbons (CH$_4$, C$_2$H$_4$) were analyzed by Porapak Q column with FID detector. N$_2$ in the gas was used as internal standard to calculate CH$_4$ and CO$_2$ conversions. The trace naphthalene and tar converted products were analyzed by HP-1 column in Agilent 6890/5973 GC–MS with Entech 7100 pre-concentration system.

### 2.3. Biomass gasification-reforming procedure

As shown in Fig. 2, the system was mainly made up by biomass feeder, fluidized-bed gasifier, downer reactor, reformer, water bath, gas tank. Pine sawdust of 200–250 kg/h was air-gasified. The raw fuel gas passed through a purification unit to separate raw fuel gas (H$_2$/CO/C$_2$H$_4$/N$_2$) was desulfurized and dried. The gas was washed by water to eliminate ash particles and other impurities and pumped by roots blower to gas tank for dimethyl ether synthesis.

### 2.4. Catalyst characterization

The elemental compositions of the catalysts were determined by inductively coupled plasma-atomic emission spectroscopy (ICP-AES) on a PEPLASMA-2000 instrument. X-ray diffraction (XRD) patterns were obtained on a BDX3300 using CuK$\alpha$ radiation at 40 kV and 30 mA. The thermogravimetric (TG) analysis of the spent catalyst was performed on a STA409PC (Netzsch Instruments) in a temperature range of 40–900°C at the heating rate of 10°C/min in air condition.

### 3. Results and discussion

#### 3.1. Effect of Ni/Mg mole ratio of MCNiMgO on reforming activities for model biomass fuel gas

In the process of reforming model biomass fuel gas, simultaneous CO$_2$ reforming of hydrocarbons (tar, CH$_4$, C$_2$ and other light hydrocarbons), reverse water–gas shift (WGS) and carbon deposition reactions were conducted as Eqs. (1)–(6) present.

\[
\text{CH}_4 + \text{CO}_2 = 2\text{CO} + 2\text{H}_2 \quad (1)
\]

\[
\text{C}_2\text{H}_4 + 2\text{CO}_2 = 4\text{CO} + 2\text{H}_2 \quad (2)
\]

\[
\text{C}_{10}\text{H}_8 + 10\text{CO}_2 = 4\text{H}_2 + 20\text{CO} \quad (3)
\]

\[
\text{CO}_2 + \text{H}_2 = \text{CO} + \text{H}_2\text{O} \quad (4)
\]

\[
2\text{CO} = \text{C} + \text{CO}_2 \quad (5)
\]

\[
\text{CH}_4 = \text{C} + \text{H}_2 \quad (6)
\]

The dry reforming activities as a function of temperature over different MCNiMgO are shown in Fig. 3. CH$_4$, CO$_2$ and tar conversions increased with the increased temperature over all three catalysts due to the endothermic reforming reactions and reverse WGS [16]. CO and H$_2$ yields increased consequently in Fig. 3c and d.

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>NiO (wt.%)</th>
<th>MgO (wt.%)</th>
<th>Cordierite (wt.%)</th>
<th>Al$_2$O$_3$ (wt.%)</th>
<th>Ni/Mg (mole ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCNi$<em>{0.48}$Mg$</em>{0.52}$O</td>
<td>5.7</td>
<td>4.7</td>
<td>84.6</td>
<td>6.2</td>
<td>0.40/0.60</td>
</tr>
<tr>
<td>MCNi$<em>{0.51}$Mg$</em>{0.49}$O</td>
<td>8.3</td>
<td>4.3</td>
<td>84.0</td>
<td>3.4</td>
<td>0.51/0.49</td>
</tr>
<tr>
<td>MCNi$<em>{0.62}$Mg$</em>{0.38}$O</td>
<td>10.4</td>
<td>3.4</td>
<td>85.6</td>
<td>1.6</td>
<td>0.62/0.38</td>
</tr>
</tbody>
</table>
Fig. 2. Schematic diagram of biomass gasification–reforming system.

Fig. 3. Dry reforming performance of model biomass fuel gas over MCNiMgO (■ MCNi0.40Mg0.60O; ● MCNi0.50Mg0.50O; ▲ MCNi0.60Mg0.40O): (a) CH₄ conversion; (b) CO₂ conversion; (c) CO yield; (d) H₂ yield; (e) H₂/CO ratio in tail gas; (f) Naphthalene conversion over MCNi0.51Mg0.49O.
For MCNi0.40Mg0.60O, MCNi0.51Mg0.49O and MCNi0.62Mg0.38O, CH4 and CO2 conversions were less than 60% when temperature was below 650 °C, and Ni/Mg mole ratio of MCNiMgO show no obvious effect on the conversions, especially for CH4 conversion. The same trends were observed as temperature increased above 830 °C with more than 93% and 85% of CH4 and CO2 conversions respectively. It could attribute to the incomplete activation of catalysts below 650 °C and the reaction equilibrium above 830 °C [17,18]. Thus Ni/Mg ratio of MCNiMgO was the main influencing factor at 650–830 °C.

In this context, the impregnation of Ni, Mg on the monolith substrates and the high calcination temperature at 850 °C brought to NiO–MgO solid solution structure formation, which was more difficult to be reduced than pure NiO [19]. But the partially reducible NiO–MgO solid solution seems to result in high Ni dispersion and small Ni particles to stabilize the reduced nickel surfaces from carbon deposition with high activity [16]. MCNi0.51Mg0.49O with Ni/Mg mole ratio of 0.51:0.49 exhibited high CH4 conversion of 87.2% at 750 °C, probably derived from the forming of NiO–MgO solid solution structure on the monolithic surface(shown by calcined catalyst in Fig. 4) [20]. And the isolation effect of MgO during reduction and reformation is critical to the formation of highly dispersed active Ni0 particles in the solid solution [19]. The lower CH4 conversion of MCNi0.62Mg0.38O than MCNi0.40Mg0.60O and MCNi0.51Mg0.49O at 700–830 °C was probably due to its easy reducibility from high NiO concentration (10.4 wt%) and weak MgO isolation effect, which resulted in low Ni0 dispersion, low anti-carbon deposition ability and decreased CH4/CO2 reforming activities [21,22].

Yet the agglomerated Ni0 particles of MCNi0.62Mg0.38O decreased the interaction between Ni and support, and increased the explosion of MgO, which related to the surface basicity and the activation of CO2 [21]. In the same time, the low Ni0 dispersion could also accelerate reverse WGS reaction [23], which resulted in the highest CO2 conversion and CO yield for MCNi0.62Mg0.38O, shown in Fig. 3b and c.

The increasing H2 yield with the increased temperature consisted with the increasing CH4 conversion trends, shown in Fig. 3d. It was because H2 was produced from CH4 and naphthalene conversion, where CH4 was the main source [24]. High CH4 conversion over MCNi0.51Mg0.49O resulted in high H2 yield at 700–800 °C, which was 65.2% at 750 °C.

H2/CO ratio in the tail gas kept decreasing with enhanced temperature and the ratio was the lowest over MCNi0.62Mg0.38O at same temperature, which decreased from 1.37 to 0.78 at 500–850 °C. This phenomenon further confirmed that endothermic reverse WGS occurred simultaneously, which produced CO by consuming H2 on the agglomerated Ni0 particles.

Naphthalene conversion over MCNi0.51Mg0.49O increased from 48.2% to 94.2% at 500–750 °C in Fig. 3f. As temperature was above 830 °C, the increasing tendency slowed down due to the equilibrium of endothermic naphthalene reforming reaction. Corella reported that tar conversion rate of his monolithic catalysts in real fuel gas cleaning was 21–96%, depending on operation condition [7]. The use of clean model biomass fuel gas might be the main reason for the higher naphthalene conversion in this context.

From the reforming results above, it could be concluded that dry reforming of model biomass fuel gas is a complicated system, including coupling reactions over MCNiMgO. So it is hard to optimize the catalysts. While in biomass to liquid fuel conversion process, the main purpose of reforming raw fuel gas is to produce considerable H2 for CO hydrogenation [25]. From this point of view, high H2 yield of MCNi0.51Mg0.49O with adequate Ni0 active centers for CH4 reforming was chosen for the following experiment and the temperature of 750 °C was preferred due to the proper H2/CO ratio in tail gas and adequate CH4 and CO2 conversion activities.

### 3.2. Stability of MCNi0.51Mg0.49O in dry reforming of model biomass fuel gas

It is known that the deactivation of Ni-based catalyst was serious during reforming, due to carbon deposition via Boudouard and methane decomposition reactions. To investigate the stability of MCNi0.51Mg0.49O, the reforming experiment was carried out at 750 °C for a long time and the results are shown in Fig. 5.

The pressure drop was hardly detectable during 60 h time on stream (TOS), which resulted from nearly 95% of naphthalene conversion in Fig. 3f and slight carbon deposition on MCNi0.51Mg0.49O. In the same time, the open channels of monolithic catalyst were
not easily blocked as traditional powdery or cylindrical catalysts do, which could keep stable pressure drop in the reactor and make them a prominent support substrate for Ni reforming catalyst [26]. CH4 conversion maintained about 88% after 60 h TOS, while CO2 conversion decreased slowly from 70.1% to 56.2%. And tail gas composition changed slightly: CH4 content increased from 1.03 vol% to 1.38 vol%, H2 content was almost the same of 32.0% and CO2 content increased from 4.60% to 7.37% in Fig. 5c. The H2/CO ratio in the tail gas was about 1 and the content of H2 or CO were higher than 30 vol% after 60 h TOS. The formation of solid solution and highly dispersed Ni0 particles on the surface of MCNi0.51Mg0.49 might be the main reason for the stable reforming activity, confirmed by the XRD patterns in Fig. 4.

The XRD pattern of calcined MCNi0.51Mg0.49 exhibits obvious presence of NiO (2θ = 37.1°, 43.3°, 62.8°) and the peaks at 36.8°, 44.9° and 65.3° were identified as NiMgO2, which confirmed the formation of NiO–MgO solid solution structure during calcination. The weak diffraction intensity at NiO at 44.3°, 51.8° and 76.5° for the reduced catalyst indicates small Ni crystallite size and high dispersion of Ni0 particles on the surface [22]. In the same time, due to the stability of NiO–MgO solid solution and partial reduction, its phase can still be detected in the reduced and spent MCNi0.51Mg0.49. The existence of NiO diffraction lines for the reduced and spent MCNi0.51Mg0.49 contributed to the re-oxidation of metal Ni0 under atmosphere condition during XRD analysis. The increased Ni0 diffraction intensity at 44.3° for the spent MCNi0.51Mg0.49 was due to the further reduction of NiO–MgO solid solution by high H2 content (16.0 vol%) in the feed gas. Yet due to the co-existence of NiO–MgO solid solution and the isolation effect of support substrate, the agglomerated active Ni0 particles were kept from sintering, which provided high CH4 conversion activity as well as stability over a long operation time. And after 2 h’s recalcination of spent MCNi0.51Mg0.49 in air at 800 °C, the weight loss was about 1.38%, indicating low carbon deposition amount. The specific structure as NiO–MgO solid solution and alkali MgO of MCNi0.51Mg0.49O, derived from 0.51:0.49 of Ni/Mg ratio, was suitable for CH4/CO2 conversion and owned anti-carbon deposition property during long time upgrading model biomass fuel gas. So this Ni/Mg ratio was chosen for preparing MCP catalyst in real biomass fuel gas reforming.

3.3. Reforming of real biomass fuel gas over MCP catalyst

3.3.1. Design and operation of the reformer

Usually the raw biomass fuel gas after gasification contains fly ash, tar and other inorganic impurities (K, Na, Ca), even after cyclone. These solid and semi-solid components deposit easily on the catalyst surface and cause high pressure drop, which is an important reactor design parameter since it represents an energy loss. To investigate the pressure drop by fly ash deposition, cold tests were carried out in one of the reformer tube, packed with blank monolith substrates (φ9.0 × 10.0 cm, 7 mm of cell spacing), under 0.51–1.75 m/s gas velocity.

For both horizontal- and vertical-placed reformer, the pressure drops increased as gas velocity increased, which were accordance with Williams’ report that the pressure drop across the monolith depends linearly on flow velocity and length [11]. And the similar pressure drops with fly ash added or not at 0.5–1.40 m/s was observed in Fig. 6a and b, attributing to the small fly ash particle size of 0.15–0.85 mm during the gasification process (confirmed by SEM) and large monolith cell spacing of 7 mm. Thus most fly ash particles could pass through the monolith cells. Further increasing gas velocity from 1.40 m/s to 1.57 m/s, the pressure drops for fly ash-added horizontal-placed reformer and without fly ash-added one were 1400 Pa and 1050 respectively and it was due to the channel blocking by partially deposited fly ash due to gravity, observed by naked eyes.

Yet for the vertical-placed reformer, the pressure drop was as low as 850 Pa at 1.57 m/s with fly ash adding amount of 330 g/m3, higher than that in the horizontal-placed reformer (210 g/m3). And the pressure drop difference in Fig. 6b was not obvious when the gas velocity increased to 1.75 m/s due to the holdup and entrainment along the gas flow direction and most fly ash was carried downward with the bulk gas flow, so the vertical-placed reformer was preferred. And the reformer with 49 tubes according to 2.1, was applied for upgrading real raw biomass fuel gas, derived from air gasification of pine sawdust (200–250 kg/h).

3.3.2. Reforming of real raw biomass fuel gas over MCP in the multi-tube reformer

Commercial diesel was combusted in the burner to provide heat for the endothermic reforming. Because of the relatively large size

Fig. 6. Pressure drop of the reformer (packed with monolith substrates (φ9.0 × 10.0 cm, 7 mm cell spacing)) during cold test (□ without ash; ● with ash): (a) horizontal-placed reformer (fly ash adding amount 210 g/m3); (b) vertical-placed reformer (fly ash adding amount: 330 g/m3).

Fig. 7. Temperature of the multi-tube reformer (A: tube wall; B: catalyst tube; C: difference between A and B).
of the reformer, thermal delay and low thermal transferring efficiency of the parallel channel monolith [11,27], there was temperature difference between tube wall and catalyst tube, especially during the initial 2 h heating (more than 300 °C) as shown in Fig. 7. And the difference decreased slowly to 120 °C after 4 h operation and kept stable at about 100 °C when the burning lasted more than 6 h. And the low MCP temperature in the tube affected the reforming performance since the reforming reactions are mostly governed by temperature [28].

It can be seen that the pressure drop of the reformer fluctuated over the first 2 h TOS and the highest pressure drop was up to 1200 Pa (Fig. 8a) due to the unstable gasification process. But after about 2 h TOS, the pressure drop kept stable of about 700 Pa and that would decrease the power requirement for roots blower, which

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Fig. 8. Typical results of reforming real biomass fuel gas over MCP: (a) pressure drop of the reformer, (b) CH₄, CO₂ and tar conversion, (c) tail gas composition.

Fig. 9. Photos of MCP: (a) fresh; (b) spent MCP after 60 h reforming real raw biomass fuel gas at 600 °C; (c) spent MCP after 2 h of re-calcination in air condition at 800 °C.

Fig. 10. TG patterns of the spent MCP at different positions of the multi-tube reformer (A: top in the tube; B: middle in the tube; C: bottom in the tube): (a) left tube; (b) right tube; (c) and (d) intermediate tubes.
ventilated biomass fuel gas to the gas tank. The reforming of real raw biomass fuel gas over MCP was obvious: CH4 conversion of raw biomass fuel gas (initial compositions: H2/CO/C2H4/CH4/CO2/N2 = 10.2/16.8/0.5/6.4/15.2/51.0, vol.% in Fig. 7C) was above 84% during 60 h TOS in Fig. 8b. CO2 conversion was relatively low to be below 40%. The conversion values were lower than those of MCNi0.51Mg0.49O for model biomass fuel gas reforming in Fig. 3a and b due to inadequate external heat transfer of the burner and the low reforming temperature at 670°C. Yet tar content decreased from 4.8–5.3 g/m3 to 0.12–0.14 g/m3 after catalytic reforming, which resulted in more than 40 vol% content of H2 and CO with H2/CO ratio of around 1, higher than the original content of 27 vol%.

3.3.3. Characterization of the spent MCP
It can be seen that the surface of spent MCP after 60 h TOS was covered with fly ash and black particles in Fig. 9, but its open channels could keep the stable pressure drop in Fig. 8a. TG patterns of the spent MCP are presented in Fig. 10 and the weight loss at any position of the reformer was less than 5%, indicating low carbon deposition degree.

It can also be seen that the weight losses for the spent MCP in the left and right tubes of the reformer were more serious than those in the intermediate tubes. For example, the MCP weight loss in the middle of the left, right and intermediate tube was 3.82 wt%, 3.28 wt% and 0.15 wt% respectively, shown in Fig. 10a–c. It resulted from the good thermal transferring in the intermediate tubes, where the burner was assembled facing to the reformer and that relatively high reforming temperature decreased carbon deposition degree on MCP surface.

The similar XRD patterns of spent MCP at different positions of the multi-tube reformer in Fig. 11 also indicated that Ni0 agglomeration was not likely occurred during reforming operation and active Ni particles of MCP kept stable due to the NiO–MgO solid solution structure as described in Section 3.2.

And the deterioration of inorganic impurities like alkali compounds in fly ash from fluidized gasification of pine sawdust is another adverse factor on reforming performance, which would form aerosol particles and deposit on reforming catalyst or foul the downstream reformer [29]. So the K and Na contents in the spent MCP were analyzed by ICP-AES and list in Table 2, which were similar of 0.03–0.07 wt% except at the reformer inlet (0.26 wt% and 0.11 wt% respectively). It was because of the relative vicinity to the gasifier, where high concentrations of K and Na in the fly ash were inclined to deposit. And due to the low alkali content in the reformer during practical gasification, CH4 conversion, the yields to H2 and CO kept high after 60 h operation in Fig. 8.

4. Conclusion
Upgrading model biomass fuel gas in a lab-scale stainless steel tubular reactor and real raw biomass fuel gas in a multi-tube reformer have proved that the advantages of using monolithic catalyst-packed reactor are notable: high catalytic performance per unit mass of active metal, high operating stability and low-pressure drop of catalytic reactor. And the NiO–MgO solid solution structure on the monolithic surface was the main reason for good CH4 conversion and H2 yield, which restrained the active Ni0 centers from agglomeration and kept it in high dispersion. Thus carbon deposition was decreased when the Ni/Mg mole ratio was optimized to be 0.51:0.49 with 8.3 wt% of NiO. The reforming process in the pilot-scale plant (200–250 kg/h of pine sawdust feed rate) was tested to be feasible for produce biomass synthesis gas with more than 40 vol% content of H2 and CO with H2/CO ratio of around 1, higher than the original content of 27 vol%. Yet due to the large size of the multi-tube reformer and low thermal transfer efficiency of monolith substrates, the temperature in the catalyst tube was relatively low. And the modifications of the reformer to increase burner efficiency and direct dimethyl ether synthesis process are ongoing by our group.

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