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Catalytic Cracking of Tar Derived From Rice Hull Gasification over Palygorskite-Supported Ni and Fe

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Abstract

The catalytic performance of Ni-Fe/PG (PG: palygorskite) catalysts pre-calcined and reduced at 500 °C for catalytic decomposition of tar derived through rice hull gasification was investigated. The materials were characterized using X-ray diffraction, hydrogen temperature reduction, transmission electron microscopy. The results showed that ferrites with spinel structure ((Ni²⁺, Fe)₃O₄) were formed during preparation of bimetallic systems during calcination and reduction of the precursors (Ni-Fe/PG catalysts) and NiO metal oxide particles were formed over Ni9-Fe6/PG catalyst. The obtained experimental data presented that Ni-Fe/PG catalysts had greater catalytic activity than natural PG. Tar removal using Ni9-Fe6/PG catalyst was as high as Fe10-Ni6/PG catalyst (99.5 %). Ni9-Fe6/PG showed greater catalytic activity with greater H₂ yield and showed stronger resistance to carbon deposition, attributed to the presence of NiO nanoparticles. Thus, the addition of nickel and iron oxides played an important role in catalytic cracking of biomass tar.

Keywords

Palygorskite clay, Nickel oxide, Catalytic cracking, Biomass tar, Hydrogen production

1. Introduction

Biomass gasification offers the potential for producing a fuel gas that can be used for power generation or synthesis gas applications. Pyrolysis of biomass has several environmental advantages over fossil fuels: namely lower emission of CO₂ and other greenhouse gases [1]. However, one of the major issues in biomass gasification is dealing efficiently with tar reduction during the pyrolysis process. This presents significant impediment to the application of biomass gasification. The condensed compounds present in tar may cause problems in downstream handling, making catalytic hot gas cleaning a necessary step in most gasification applications. Catalytic decomposition appears to be a very attractive way to convert tar components into H₂, CO and other useful chemicals.

Most research has focused on steam reforming of various hydrocarbon feedstock over supported-Ni and expensive metal catalysts [2-8]. Furusawa et al. [9] reported that Co/MgO catalyst had higher activity than any types of Ni/MgO catalysts. This was attributed to the difference in catalytic performance between Co/MgO and Ni/MgO. Asadullaha et al. [10] reported that almost all carbon in the biomass was converted into gas products using Rh/CeO₂/SiO₂ catalysts and the deactivation of the catalyst caused by carbon or char deposition on the catalyst surface was not severe. On the other hand, Rh/CeO₂/SiO₂ catalysts have some disadvantages due to the high cost of Rh and the limited availability of this expensive metal. In general, Ni catalysts showed high catalytic activity for the removal of tar and are very efficient in tar removal. However, coking on the catalyst surface and sintering of Ni particles caused the loss of the catalytic activity [11]. In addition, to avoid a fast deactivation of Ni catalyst by coke, researchers used CeO₂ as a catalyst additive. It is well known that CeO₂ supported catalysts can promote the reaction of active carbon with O₂ enhancing the catalytic activity and resistance to coking [12-14].

The motivation for this work is to find a new catalyst system, such as a binary catalyst, which can not only replace nickel catalyst but also the expensive metal catalyst Rh. For the catalyst, it is expected that the interaction of two kinds of metal oxides play an important role in the catalytic decomposition of biomass tar derived from biomass gasification. Thus, this present work focuses on the investigation of using iron and nickel oxide catalysts supported on palygorskite clays for tar removal instead of single nickel catalyst or expensive metal catalysts. Little research has been undertaken using iron catalysts, including the binary oxide catalyst of iron and nickel oxides for tar removal [15, 16]. The steam reforming of methane has been studied over 1 wt%Fe/ZrO₂ catalyst but

53 low methane conversion was measured at 800 °C [15]. Uddin et al [16] reported that the activity of
54 the iron oxide catalysts for tar decomposition seemed stable with cyclic use but the activity of the
55 catalysts for the water gas shift reaction decreased with repeated use. Palygorskite clay (PG), a
56 hydrated magnesium aluminosilicate, shows high crystallinity, large pore diameter (2.8 nm) and high
57 specific surface area (228.5 m²/g) [17]. In general, it consists of 65.5 wt % SiO₂, 5.4 wt % Al₂O₃, 14
58 wt % MgO, 3.2 wt % Fe₂O₃ and trace amounts of other minerals. Thus, palygorskite clays have
59 proven to be a useful support.

60 Previous research has focused on the effect of temperature on catalytic bed and catalyst
61 loadings for tar decomposition. On the basis of previous research, the application of
62 palygorskite-supported Ni and Fe oxides are investigated in the present work. The purpose of this
63 study is to prepare Fe-Ni/PG catalysts and determine the catalytic performances of Ni-Fe/PG catalysts
64 for tar removal derived from rice hull gasification.

65

66 2. Experimental

67 2.1. Preparation of the catalysts

68 Palygorskite-supported nickel and iron oxides catalysts were prepared by incipient wetness
69 impregnation of palygorskite with aqueous solutions of Ni(NO₃)₂·6H₂O and Fe(NO₃)₃·9H₂O, followed
70 by overnight drying at 105 °C. For the catalyst testing, all catalysts were pelletized, crushed and
71 sieved to 0.85–0.425 mm, followed by calcination in air for 2 h at 500 °C. The reaction product was
72 then reduced in hydrogen, derived from a hydrogen generator at a flow rate of 80 ml·min⁻¹, and held at
73 500 °C for 1 h. The amount of nickel and nickel oxide loading on the catalyst support was controlled
74 between 0 and 12 wt% by changing the concentration of Ni(NO₃)₂·6H₂O and Fe(NO₃)₃·9H₂O
75 solutions. In this study, Ni_x-Fe_y/PG (x=0 wt%, 3 wt%, 6 wt%, 9 wt%, 12 wt%, when the y=6 wt%;
76 y=0 wt%, 1 wt%, 6 wt%, 8 wt%, 10 wt%, 12 wt%, while x=6 wt%) were prepared for catalyst testing.

77

78 2.2. Catalytic testing

79 Biomass tar, catalyzed to produce H₂-rich, was derived from rice hull gasification. The tar
80 consists of C 79.2 wt%, H 5.3 wt%, N 1.6 wt%, O 7.4 wt%, ash 5.3 wt% and a small amount of the
81 elements Cl and S.

82 Catalytic tests were controlled by using the fixed-bed experimental system shown in Fig. 1. The
83 setup consists of three kinds of operations a) sample injection system including biomass tar and
84 carrier gas, b) reaction and collection system and c) analysis system. The reactor used was a straight
85 quartz tube (id. 30 mm width and 400 mm body length) and the catalyst bed was supported by means
86 of quartz wool. All the catalysts were tested under the same experimental conditions: WHSV = 2.7 h⁻¹
87 and atmospheric pressure. Nitrogen was used to carry the biomass tar cracking gases into and out of
88 the reactor; the flow rate of nitrogen was 80 ml·min⁻¹ carrying 0.45 g·min⁻¹ of biomass tar. The rice
89 hull gasification tar was introduced into the reactor with a peristaltic pump (BQ50-1J). Granular
90 activated carbon (GAC) was used for collecting unreacted tar and by-products as shown in Fig. 1.
91 Almost all the unreacted and by-products can be adsorbed by GAC. In this way, unreacted tar and
92 byproducts are recovered using GAC and the amount of unreacted tar and byproducts were calculated
93 by subtracting the mass of the filter before reaction from that remaining after reaction. Thus, the
94 efficiency of catalysts on biomass tar can be calculated by the following formula. In the formula,
95 M_{in-tar} and M_{out-tar} represent the amount of tar introduced into the reactor and tar collected in the filter,
96 respectively.

$$97 \text{ Tar removal} = \frac{M_{in-tar} - M_{out-tar}}{M_{in-tar}} \times 100\%$$

98 After the reaction, the peristaltic pump was closed down and products were blown off with
99 nitrogen at the reaction temperature into an air cell and the gas volume was determined by a wet test
100 meter. Subsequently the catalysts were cooled down to room temperature for further characterization.
101 The non-condensable gases, which included hydrogen, nitrogen, carbon monoxide and methane were
102 analyzed by gas chromatography (GC-7890T) equipped with a C2000 column and a thermal

103 conductivity detector (TCD) with argon as carrier gas to measure H₂, N₂, CO and CH₄. The column
104 temperature, evaporation chamber temperature, the temperature and bridge current of detector were 70
105 °C, 120 °C, 100 °C, 100 mA, respectively. Hydrogen yield was calculated using the following
106 formula. M_{H-out} and M_{H-in} represent the mass of hydrogen input reactor and in catalytic cracking tar,
107 respectively.

$$108 \text{ Hydrogen yield} = \frac{M_{H-out}}{M_{H-in}} \times 100 \%$$

109

110 2.3. Catalyst characterization

111 X-ray diffraction (XRD) measurement was performed on a Rigaku powder diffractometer with
112 Cu K α radiation. The tube voltage was 40 kV, and the current was 100 mA. The XRD diffraction
113 patterns were taken in the range of 5-70° at a scan speed of 4° min⁻¹, which was used for identifying
114 nickel and iron oxides as well as their oxidation states on the surface of the palygorskite. Phase
115 identification was carried out by comparison with a database

116 H₂-temperature programmed reduction (TPR) measurements were performed on calcined
117 samples under 5 % flowing H₂ diluted with Ar using an electric oven-temperature programmed
118 apparatus to investigate the nickel and iron oxide phases after calcination. A 60 ml·min⁻¹ feed of 5 %
119 H₂/Ar was used for reduction and the temperature was ramped at 10 °C min⁻¹ to 850 °C. The effluent
120 gases from the reactor were conducted to flow directly into the mass spectrograph (MS, Hiden
121 QIC-20), which measured the consumption of H₂

122 HRTEM measurements were made by a JEOL 2010 microscope with an energy dispersive
123 X-ray (EDX) facility. Total carbon (TC) measurement was performed under flowing O₂ to determine
124 the amount of total carbon deposition on the catalyst. A 50 ml·min⁻¹ feed of O₂ was used to convert
125 carbon into carbon dioxide when the temperature was controlled at 1000 °C.

126

127 3. Results and discussion

128 3.1. Characterization of prepared catalysts

129 3.1.1 XRD

130 The XRD patterns of reduced catalysts with various Ni loading amounts (0, 3, 6, 9 and 12 wt. %)
131 supported on Fe6/PG are presented in Fig. 2. The XRD patterns were normalized by the palygorskite
132 peak at 26.6°. The peak at 44.7° is assigned to Fe. No peaks related to Ni, NiO, or (Ni, Fe) were
133 observed at all in Fig. 2(e). In addition, the peak at 61.3° was observed and identified as Fe_{0.942}O, but
134 intensity of the peak was very low compared with the Fe peak observed in Fig. 2(a). This indicated
135 that Fe₂O₃ was not reduced to Fe completely. The reason is attributed to the low temperature (500 °C)
136 because reduction of Fe₂O₃ is known to occur in two steps [18]. This was observed from the following
137 TPR results (Fig. 4(g)). From other profiles of catalysts in Fig. 2, it can be seen that the peak of
138 ferrites with spinel structure (Ni[□], Fe)₃O₄ is observed at 2 θ =35.34° and the peaks corresponding to (Ni,
139 Fe) are observed at 2 θ =44°, 51.2° except the peak of Fe_{0.942}O. Further, the peak at 2 θ =62.64° assigned
140 to NiO is observed for Ni loaded catalysts. The peaks at 37.2° and 43.1° corresponding to NiO were
141 also observed except the peak at 2 θ =62.6°. The peak at 2 θ =44°, 62.6°, assigned to the alloy of (Ni,
142 Fe), NiO respectively, become more intense and then less intense with increasing Ni loading.

143 Fig. 3 shows the XRD patterns of various Fe loading amounts (0, 1, 6, 8, 10, 12 wt %) on
144 Ni6/PG catalyst. Three major peaks at 8.4°, 19.7°, 61.4° were indentified as PG and the diffraction
145 peak corresponding to PG becomes more intense with decreasing Fe loading. Additionally, the peak at
146 35.5° was observed and indentified as due to PG in Fig. 3(f). The peak increased in intensity as Fe
147 was supported on Ni6/PG. The peaks at 30.2°, 35.5°, 43.7°, 57.2°, 62.6° were observed and these were
148 identified as (Ni[□], Fe)₃O₄. The intensities of these peaks assigned to (Ni[□], Fe)₃O₄ increased with an
149 increase in Fe loading amount. When (Ni[□], Fe)₃O₄ particle size are calculated by the Sherrer equation
150 using XRD peak widths, the particle size were found to be 13.1 nm, 5.1 nm, 4.7 nm for the catalysts
151 of Ni6-Fe12/PG, Ni6-Fe10/PG, Ni6-Fe8/PG. The size increase is associated with the aggregation of
152 (Ni[□], Fe)₃O₄ particles in the catalyst with increasing Fe content. These values are less than the

153 diameter of palygorskite (about 40 nm) [17]. So, this kind of particle can dispersed on the surfaces of
154 palygorskite. This kind of dispersion is in good agreement with the following TEM images.
155 Furthermore, the peak at 44.6°, assigned to the alloy of Fe and Ni, increased in intensity with an
156 increase in Fe loading.

157 3.1.2 TPR

158 H₂-TPR profiles of PG and Nix-Fe6/PG (x=0, 3, 6, 9, 12) catalysts are presented in Fig. 4.
159 These curves were largely different from the typical TPR traces of Fe₂O₃, possibly due to difference in
160 interaction between the PG, Fe₂O₃ and NiO. It is observed from the Fig. 4 that PG presents a poorly
161 resolved peak in the 380-750 °C range. In the case of Fe₂O₃ trace shown in Fig. 4 g, a fraction of the
162 first peak is assigned to the conversion of Fe₂O₃ to Fe₃O₄, and the second is assigned to the reduction
163 of Fe₃O₄ to Fe⁰ [19, 20]. However, there were three kinds of poorly resolved peaks found in Fig. 4
164 when Fe was loaded on PG, which mainly results from the interaction between Fe₂O₃ and PG [21].
165 The first peak (T= 325 °C) corresponds with the reduction of Fe₂O₃ and/or NiO crystallites. The
166 intensity decreases as the NiO is loaded on the Fe6/PG resulting from the interaction between NiO
167 and Fe₂O₃. The intensity increases when NiO loading is over 3 wt% occurs, resulting from excessive
168 NiO (without participating in the interaction with Fe₂O₃). The second peak (T=500 °C) and a large
169 shoulder peak is related to the reduction of Fe₂O₃ with strong interaction with PG, Fe₂O₃ with NiO.
170 The reduction temperature decreased from 500 °C to 450 °C with the increasing Ni loading. The shift
171 of the peak to lower temperature for higher Ni content on Fe6/PG catalyst is attributed to the decrease
172 of the interaction between NiO and Fe₂O₃, which resulted from better dispersion of NiO on the PG
173 [22]. The third reduction peak (T=740 °C) appears for all supported PG catalysts, associated with the
174 conversion of Ni ions to Ni and/or Fe ions to Fe ((Ni[□], Fe)₃O₄, Fe_{0.942}O, alloy of Fe and Ni (Fe Ni)).
175 Compared with the Fe₂O₃, the reduction temperature of Nix-Fe6/PG decreased obviously, which is
176 attributed to the dispersion of Fe₂O₃ on the PG.

177 Fig. 5 shows the H₂-TPR of PG and Fey-Ni6/PG (y=0, 1, 6, 10, 12) catalysts. These curves are
178 largely different with typical H₂-TPR traces of NiO, due to different interactions between the PG,
179 Fe₂O₃ and NiO. There were four kinds of reduction peaks observed in Fig.5. The first peak (T= 325 °
180 C) corresponds with the reduction of small particle size Fe₂O₃ and/or NiO crystallites. This peak
181 decreases in intensity as Fe₂O₃ is introduced into the Ni6/PG catalyst resulting from the interaction
182 between NiO and Fe₂O₃ and appear again when Fe loading is over 3 wt% resulting from excessive
183 Fe₂O₃ (without participating in the interaction with NiO). The explanation of the second peak can be
184 obtained from Fig.1. The third and forth peak could be attributed to the reduction process of Fe₃O₄
185 and (Ni[□], Fe)₃O₄, respectively.

186 3.1.3 TEM

187 Fig. 6 shows the HRTEM images of Ni6-Fe6/PG after H₂ reduction pretreatment at 500 °C.
188 The shape of palygorskite (diameter between 20~40 nm) can be seen clearly in Fig. 6. In addition,
189 small particles (<30 nm) can be observed on Ni6-Fe6/PG catalyst (Fig. 6c). The chemical composition
190 of palygorskite and such agglomerates were studied by Energy Dispersive X-ray (EDX) spectroscopy
191 and analysis (Fig. 6 a, b). According to the data obtained by EDX, palygorskite consisted of Mg, Al,
192 Si, Fe, O and Ni6-Fe6/PG was composed of Mg, Al, Si, Fe, O, Ni and Cu (from copper net). These
193 data confirmed the role of Fe (Fe₂O₃) and/or Ni (NiO) in catalytic decomposition of biomass
194 gasification tar.

196 3.2 Catalytic performance of Ni loading supported on Fe6/PG

197 Fig. 7 presents the results of the H₂ yield obtained at 700 °C after steady state was achieved (20
198 min on reaction system) over different catalysts including PG, Nix-Fe6/PG (x=0, 3, 6, 9, 12).
199 Non-reactive quartz sand was used as a catalyst test blank. Catalysts with varying Ni loading on
200 Fe6/PG were prepared by the incipient wetness impregnation method (see Section 2.1). Tar removal
201 and hydrogen yield were increased and then decreased with the increasing Ni loading. The tar removal
202 and hydrogen yield showed the highest amount as Ni supported on Fe6/PG catalyst was 9 wt%. Tar
203 removal of Ni9-Fe6/PG catalyst, Fe6/PG, SiO₂ reached 99.1 %, 59.7 %, 26.9 % and hydrogen rate of
204 production reached 86.3 %, 35.4%, 8.9%, respectively. This indicated that Ni9-Fe6/PG showed the

205 best result of tar removal and catalytic cracking activity for rice hull gasification tar to product H₂-rich
206 gas. But the hydrogen yield decreased when Ni loading was over 9 wt% [23, 24].

207 In addition, the TC of reacted catalysts is presented in Fig. 7. It shows that the TC increased
208 when Ni was loaded on Fe6/PG, but carbon deposit on Ni_x-Fe6/PG (3, 6, 9, 12) almost keep the same
209 level. It can be explained by the presence of NiO, observed in Fig. 2. The content of CO in the
210 gaseous products increased with increasing Ni loading. This increase appeared to be significant when
211 Ni loading increased from 3 to 6 wt%. In conclusion, NiO played a critical role in decreasing the
212 carbon deposit and increasing the amount of CO in the gaseous product.

213 As seen from the XRD results (Fig. 2), the intensities of these peaks assigned to Fe_{0.942}O and
214 alloy of Fe and Ni increased with increasing Fe loading. Based on the results of TPR (Fig. 4), Fe³⁺ has
215 been partially reduced to Fe²⁺ or Fe under 500 °C before catalytic reaction. Many researchers have
216 verified the catalytic activity of Iron oxide on catalytic cracking biomass gasification tar [16]. Besides,
217 there was a strong interaction between NiO and Fe₂O₃ at the stage of calcination and reduction of
218 bimetal system, which leads to solid-solid interaction between Fe₂O₃ and NiO forming a spinel (Ni[□],
219 Fe)₃O₄ crystalline phase. The excess NiO appeared as crystalline NiO [25, 26]. It can be speculated
220 that the initial reduction of Fe³⁺ to Fe²⁺ or Fe enhanced hydrogen yield [19]. The decrease of carbon
221 deposit on the Ni9-Fe6/PG is ascribed to the presence of NiO (Fig. 2), because NiO is resistant to
222 carbon deposition [27]. This may be the reason for the Ni9-Fe6/PG catalyst showing the best catalytic
223 activity and resistance to carbon deposit when compared with the other Ni_x-Fe6 catalysts.

224 The effect of Ni loading on the composition of gaseous products is presented in Table.1. It
225 showed that the yield of carbon monoxide increased with an increase in Ni loading. The increase of
226 carbon monoxide is less when the Ni loading amounts to more than 3 wt%. The methane yield in
227 gaseous products comes to the highest value when Ni loading is 9 wt%.

228

229 3.3 Catalytic performance of Fe loading supported on Ni6/PG

230 Fig. 8 shows the results of H₂ yield obtained at 700 °C after steady state was achieved (20 min
231 on reaction system) over different catalysts including PG, Fe_y-Ni6/PG(y=0, 1, 6, 8, 10, 12). Tar
232 removal and hydrogen yield went through a maximum with the Fe loading at 10 wt%. When
233 Fe10-Ni6/PG, Ni6/PG, SiO₂ were used as catalysts for catalytic decomposition of biomass tar, tar
234 removal reached 99.5 %, 64.4 %, 26.9 % and hydrogen rate of production reached 75.6 %, 16.7%,
235 8.9%. These results proved that Fe10-Ni6/PG showed the best results for tar removal and catalytic
236 cracking activity for rice hull gasification tar to produce H₂-rich gas.

237 Based on the results of Fig. 3, it is proposed that a monotonic increase in (Ni[□], Fe)₃O₄ alloy that
238 largely affects the catalytic reaction with increasing Fe loading. The most important parameter that
239 affects the catalytic reaction can't be confirmed under present experimental conditions and requires
240 further research. Results of research [25] has shown that the spinel phase of MgAl₂O₄ seemed to be
241 practically inactive in steam reforming reaction, but this does not prove that the spinel phase of (Ni[□],
242 Fe)₃O₄ was non-active in this catalytic cracking biomass tar. However, it was well known that the
243 particle size of (Ni[□], Fe)₃O₄ increased with increasing Fe loading. Especially, this increase appeared
244 to be significant when Fe loading increased from 10 to 12 wt%. Additionally, the reduction of bimetal
245 catalysts resulted in the formation of alloys (Fe, Ni). The structure of their crystal lattices, their
246 parameters and crystallite sizes depend on the concentration of the added metal [25].

247 In addition, TC of reacted catalysts is presented in Fig. 8. It shown that as Fe loading increased,
248 the amount of carbon accumulation on the catalysts also increased. This is in good agreement with the
249 literature [19]. The increase appeared to be significant when Fe increased from 8 to 12 wt%. Moreover,
250 the HRTEM and XRD of the reduced catalyst Ni6-Fe6/PG showed that palygorskite crystals were
251 surrounded by large metal particles with different metal phases. The formation of nanoparticles was
252 one of the conditions for the genesis of an essential state of iron-containing catalysts for carbon
253 nanotube production [28]. So, carbon deposit is high for all reacted catalysts. Effect of Fe loading on
254 the composition of gaseous products is presented in Table 2. Table 2 shows that hydrogen was the
255 main component in the gaseous products.

256 Comparing the carbon deposits as shown in Figs. 7 and 8, it is observed that carbon deposition

257 on Fe_x-Ni₆/PG catalyst was higher than Ni_y-Fe₆/PG catalysts on the whole. Obviously, it indicates
258 that the addition of Fe played a more important role compared with Ni. Figs. 7 and 8 showed the
259 effect of Ni and Fe loading on the hydrogen yield derived from catalytic cracking biomass tar. It is
260 seen that high concentration of iron can improve the conversion of carbon and high concentration
261 nickel was more favorable for the increase in yield of hydrogen. Scheme 1 shows reaction routes
262 during catalytic cracking of biomass tar over Fe-Ni/PG catalyst.
263

264 4. Conclusions

265 The following conclusions are made:

- 266 (1) The obtained experimental results and characterization (XRD, TEM, H₂-TPR) of catalysts suggest
267 that intermediate formation of ferrites with spinel structure ((Ni²⁺, Fe)₃O₄) and alloys of Fe and Ni
268 takes place on palygorskite during the preparation of bimetallic systems during calcination and
269 reduction of their precursors, which lead to increased catalytic activity. The decrease of catalytic
270 activity for biomass tar should be contributed to the increase of particles size on the PG when the
271 loading of Fe is over 9 wt% on the Ni₆/PG catalyst. The presence of NiO (Ni₉-Fe₆/PG) produces
272 the greatest activity in catalytic decomposition of tar, resistance to carbon deposition and
273 increasing content of CO in the gaseous products.
- 274 (2) The present work indicates that Fe and/or Ni play an important role in catalytic decomposition of
275 rice hull gasification tar and the support loading was found to strongly affect the catalytic
276 decomposition biomass tar for tar removal, H₂ yield and TC. The optimum loading of Fe, Ni
277 between 0 and 12 wt% for maximum H₂ yield and tar removal for catalytic cracking biomass tar
278 is 10 wt% and 9 wt%, respectively. The amount of carbon deposit increased with increasing Fe
279 (Ni) loading.
- 280 (3) Ni₉-Fe₆/PG catalyst produced greater effect on H₂ yield and resistance to carbon deposit during
281 catalytic degradation biomass tar, compared with Fe₉-Ni₆/PG. On the ground, it can be found that
282 Fe possesses better ability in improving catalyst activity in breaking down C-C and C-H bonds.
283

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287

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