Hydrotreating of Jatropha-derived Bio-oil over Mesoporous Sulfide Catalysts to Produce Drop-in Transportation Fuels

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Abstract

The bio-oil was largely produced by thermal pyrolysis of Jatropha-derived biomass wastes (denoted as Jatropha bio-oil) using a Pilot Plant with a capacity of 20 kg h\(^{-1}\) at Thailand Institute of Scientific and Technological Research (TISTR), Thailand. Jatropha bio-oil is an unconventional type of bio-oil, which is mostly composed of fatty acids, fatty acid methyl esters, fatty acid amides and derivatives, and consequently it contained large amounts of heteroatoms (oxygen ~ 20 wt.%, nitrogen ~ 5 wt.%, sulfur ~ 1000 ppm.). The heteroatoms, nitrogen especially, are highly poisonous to the metal or sulfide catalysts for upgrading of Jatropha bio-oil. To overcome this technical problem, we reported a stepwise strategy for hydrotreating of 100 wt% Jatropha bio-oil over mesoporous sulfide catalysts of CoMo/γ-Al\(_2\)O\(_3\) and NiMo/γ-Al\(_2\)O\(_3\) to produce drop-in transport fuels, such as gasoline- and diesel-like fuels. This study is very different from our recent work on co-processing of Jatropha bio-oil (ca. 10 wt%) with petroleum distillates to produce a hydrotreated oil as a diesel-like fuel (Chen et al., Catalysts 2018, 8, 59; [http://dx.doi.org/10.3390/catal8020059](http://dx.doi.org/10.3390/catal8020059)). Jatropha bio-oil was pre-treated through a slurry-type high pressure reactor under severe condition, resulting in a pre-treated Jatropha bio-oil with relatively low amounts of heteroatoms (oxygen < 20 wt.%, nitrogen < 2 wt.%, sulfur < 500 ppm.). The light and middle distillates of pre-hydrotreated Jatropha
bio oil was then separated by distillation at temperature below 240 °C, and the temperature of 240-360 °C. Deep hydrotreating of light distillates over sulfide CoMo/γ-Al2O3 catalyst was performed on a batch-type high pressure reactor at 350 °C and 7 MPa of H2 gas for 5 h. The hydrotreated oil was a gasoline-like fuel, which contained 29.5 vol.% of n-paraffins, 14.4 vol.% of iso-paraffins, 4.5 vol.% of olefins, 21.4 vol.% of naphthene compounds and 29.6 wt.% of aromatic compounds, and little amounts of heteroatoms (nearly no oxygen and sulfur, and less than 50 ppm of nitrogen), corresponding to an octane number of 44, and it would be suitable for blending with petro-gasoline. The hydrotreating of middle distillates over sulfide NiMo/γ-Al2O3 catalyst using the same reaction condition produced a hydrotreating oil with diesel-like composition, low amounts of heteroatoms (no oxygen and less than 50 ppm of sulfur and nitrogen), and a cetane number of 60, which would be suitable for use in drop-in diesel fuel.

**Keywords:** Hydrotreating, mesoporous sulfide materials, waste Jatropha biomass, drop-in biofuels, upgrading technology
1. Introduction

Biomass is one of the most abundant natural resource, which has supplied around 10% of annual primary energy consumption corresponding to a capacity of 50 EJ/yr globally in 2006-2007 [1-3]. It is generally agreed that the chemicals and fuel with low carbon footprint can be synthesized by conversion of biomass using various catalytic strategies, which contribute to the reduction of CO₂ emission and consequent avert global warming [4-10]. For example, the biodiesel fuel (BDF), which is so-called the first-generation biofuel, can be synthesized by base-catalyzed transesterification of refined vegetable oils with methanol, and it has been extensively used in the transport sector, particularly in America, European Union and ASEAN counties [6,11-16]. However, it has caused a new environmental problem in waste biomass treatment, such as discarded kernel shells and husks, which are massively produced as byproducts in the BDF industry. Recent studies have focused on post-treatment and utilization of those biomass wastes into valuable products, such as gasification to produce syngas, liquification to produce chemicals and fuels, and chip production for thermal power generation [7,17]. Similar to biomass gasification and liquification, bio-oil can be synthesized by thermal conversion of biomass, the wastes especially, through the catalytic pyrolysis or non-catalytic pyrolysis technology, and therefore it contains large amounts of heteroatom-containing
hydrocarbons, oxygen and sulfur especially, water and unwanted impurities which were highly associated with the feedstocks and the processing parameters used in the pyrolysis and condensation steps [18-21]. The subsequent upgrading of bio-oil through hydrotreating technology using metal catalysts, such as Pd/C, or sulfide catalysts, such as Co- or Ni-promoted MoS$_2$/$\gamma$-Al$_2$O$_3$, is required to remove the heteroatoms, resulting in clean and drop-in biofuel with composition and fuel property closed to petro-fuels [22]. Unfortunately, the heteroatoms, water and unwanted impurities, which are originally presented in the bio-oil, poison the active sites of metal and sulfide catalysts, causing serious catalyst deactivation and consequently reducing the quality of hydrotreated bio-oil [23-30]. Yoshimura et al. reported that the sulfide NiMo catalysts were deactivated by the oxygen-containing compounds due to the oxidation of active sites [23]. Laurent and Delmon showed that the deoxygenation of model compounds of bio-oils over CoMo and NiMo catalysts was strongly inhibited in the presence of water and ammonia [24]. There is still room for development of innovative catalytic process using advanced catalysts with high resistance to heteroatoms, which can produce clean and drop-in fuel for directly formulating with petro-fuels.

Our recent study demonstrated that Jatropha bio-oil could be synthesized by thermal pyrolysis of waste Jatropha biomass (a mixture of kernel shell and husk) using a Pilot
Plant with a capacity of ca. 20 kg/h at TISTR, Thailand [19]. The Jatropha bio-oil is an unconventional bio-oil with a high concentration of nitrogen (ca. 5 wt%) and relatively low concentrations of oxygen (ca. 20 wt%) and sulfur (<1000 ppm), which is mostly consisted of fatty acids, fatty acid methyl esters, fatty acid amides and their derivatives (> 50 wt%) in addition to other light organic compounds incorporated with heteroatoms. It is different from conventional bio-oils with high oxygen content (ca. 20-40 wt%) and low sulfur and nitrogen contents (<1 wt%), which were derived from cedar or pine biomass waste, and mostly consisted of carbohydrates and phenolic compounds. In the upgrading process, the upgraded catalysts as aforementioned were immediately deactivated by high concentration of nitrogen-containing compounds when Jatropha bio-oil was directly used as a feedstock (Scheme 1(a)). To prevent catalyst deactivation, our previous study demonstrated a co-processing method for upgrading of Jatropha bio-oil co-fed with petroleum distillates over sulfide CoMo and NiMo catalysts under severe conditions (330-350 °C and 5-7 MPa of H₂) [31]. The diesel-like fuel with nearly no heteroatoms (sulfur, oxygen and nitrogen < 10 ppm) could be obtained by hydrotreating of oil feedstock containing ca. 10 wt% of Jatropha bio-oil and ca. 90 wt% of light gas oil. In this study, a stepwise strategy was reported for hydrotreating of 100 wt% Jatropha bio-oil over sulfide catalysts to produce drop-in transport fuels including gasoline- and diesel-
like fuels (Scheme 1(b)). The Jatropha bio-oil was pre-treated by a slurry bed reactor at 400 °C and 7 MPa of H₂ using waste NiMo/γ-Al₂O₃ catalyst, followed by distillation. The clean and drop-in transport fuels were then obtained by hydrotreating of pre-treated distillates over fresh CoMo/γ-Al₂O₃ or NiMo/γ-Al₂O₃ catalysts using a high-pressure stainless-steel batch-type reactor under severe conditions. Influence of catalysts and processing parameters on the composition and fuel property of upgraded Jatropha bio-oils was reported.

Scheme 1. (a) direct hydrotreating and (b) stepwise hydrotreating of the unconventional Jatropha bio-oil.

2. Results and discussion

The sulfide CoMo/γ-Al₂O₃ or NiMo/γ-Al₂O₃ catalysts were prepared by the same procedures as reported in our previous study [30], and their structural properties were
completely studied by X-ray diffraction and absorption techniques, physisorption and chemisorption, and electron microscopes [30-33]. It has exhibited that the sulfide CoMo/γ-Al2O3 catalyst with relatively large amounts of acidic sites (NH3 uptake = 0.92 mmol g⁻¹) and coordinatively unsaturated sites (NO uptake = 0.11 mmol g⁻¹) was associated with small Co-incorporated MoS2-like slabs (4.5±1.2 nm in length and 2.0±0.53 nm in height) with relatively high stacking number (3.8±0.86) on the mesoporous alumina material. In contrast, the sulfide NiMo/γ-Al2O3 catalyst with relatively small amounts of acidic sites (NH3 uptake = 0.77 mmol g⁻¹) and coordinatively unsaturated sites (NO uptake = 0.093 mmol g⁻¹) was presumably due to large Ni-incorporated MoS2-like slabs (5.9±1.2 nm in length and 1.5±0.53 nm in height) with relatively low stacking number (2.6±0.71) on the mesoporous alumina material. In this study, the structural property of sulfide CoMo/γ-Al2O3 or NiMo/γ-Al2O3 catalysts were examined again by the wide-angle XRD pattern (Fig. 1(A)), nitrogen physisorption (Fig. 1(B)) and high-resolution transmission electron microscope (HRTEM) images (Fig. 2), in comparison to those of γ-Al2O3 as a supporting material. The XRD study shows that two diffraction peaks of Co- or Ni-incorporated MoS2-slabs are hardly observed at 20 ~ 33° and 59°, indicating that their sizes are smaller than 5 nm, and the diffraction peaks of mesoporous γ-Al2O3 framework are weakened by the impregnating. The N2 physisorption
study shows that the $H_1$ hysteresis loops of the type IV isotherms are reduced by the impregnation of Co- or Ni-incorporated MoS$_2$-slabs on the mesoporous $\gamma$-Al$_2$O$_3$ framework. The nitrogen physisorption study shows that the supporting material of $\gamma$-Al$_2$O$_3$ has surface area of 206 m$^2$ g$^{-1}$, pore volume of 0.68 cm$^3$ g$^{-1}$ and pore size of 12 nm. The sulfide CoMo/$\gamma$-Al$_2$O$_3$ or NiMo/$\gamma$-Al$_2$O$_3$ catalysts have surface areas of 204-205 m$^2$ g$^{-1}$ and pore sizes of 12 nm, which are close to those of $\gamma$-Al$_2$O$_3$ supporting material, whereas their pore volumes are decreased to 0.38-0.41 cm$^3$ g$^{-1}$. It indicates that the Co- and Ni-incorporated MoS$_2$-slabs were impregnated inside the pores of mesoporous $\gamma$-Al$_2$O$_3$ framework. The HRTEM images clearly show that the sulfide CoMo/$\gamma$-Al$_2$O$_3$ or NiMo/$\gamma$-Al$_2$O$_3$ catalysts are composed of the Co- or Ni-incorporated MoS$_2$-slabs and the mesostructured $\gamma$-Al$_2$O$_3$ particles. These results suggest that the sulfide CoMo/$\gamma$-Al$_2$O$_3$ or NiMo/$\gamma$-Al$_2$O$_3$ catalysts with well-dispersed Co- and Ni-incorporated MoS$_2$-slabs on the mesoporous $\gamma$-Al$_2$O$_3$ framework were successfully prepared.

Jatropha bio-oil was largely produced by fast pyrolysis of waste Jatropha biomass at 500 °C using a Pilot Plant equipped with an electrostatic precipitator [19]. The yields of Jatropha bio-oil, water-soluble phase and gases were 21.3, 28.6 and 50.1 wt%, respectively. Conventional bio-oil derived by fast pyrolysis of cedar or pine biomass is mostly composed of lignin-derived phenolic compounds, and it consequently contains
high concentration of oxygen (> 30 wt%) and low concentrations of sulfur (ca. 50 ppm) and nitrogen (ca. 0.1 wt%) [19,20]. However, Jatropha bio-oil is mostly composed of fatty acids, fatty acid methyl esters, fatty acid amides and derivatives, presumably due to that Jatropha oil is partly remained in the waste Jatropha biomass after the oil extraction. As a result, Jatropha bio-oil contains high concentration of nitrogen (ca. 5 wt%), relatively high concentration of sulfur (ca. 1000 ppm) and relatively low concentration of oxygen (ca. 20 wt%). The heteroatoms, nitrogen especially, are extremely poisonous to metal and sulfide catalysts used in the upgrading process [ ]. In scheme 1(a), the preliminary studies showed that direct hydrotreating of Jatropha bio-oil over sulfide and metal catalysts produced low-quality hydrotreated bio-oils with high heteroatoms, which was inapplicable for use in fuel oil blending, even if the severe conditions were used [unpublished results]. In other worlds, the sulfide and metal catalysts were immediately deactivated by strong adsorption of heteroatoms on the catalytically active sites, nitrogen especially, in the upgrading process. To solve this technical problem, we proposed a stepwise strategy for upgrading of Jatropha bio-oil over sulfide catalysts to produce drop-in biofuels (see Scheme 1(B) and Fig. 3). Jatropha bio-oil was pre-treated through a slurry-type high pressure reactor at 400 °C and 7 MPa of H2 for 2 h using 1 wt% of waste NiMo catalyst, resulting in a pre-treated Jatropha bio-oil with relatively low
concentrations of heteroatoms (oxygen < 20 wt.%, nitrogen < 2 wt.%, sulfur < 500 ppm).

The yield of pre-treated Jatropha bio-oil was around 65%. The pre-treated bio-oil was then divided into three fractions through distillation: (a) light distillates (21.0%, distillation temperature \(T_d\) < 240 °C), (ii) middle distillates (59.3%, \(T_d = 240-360\ \text{oC}\)) and (iii) heavy distillates (19.7%, \(T_d > 360\ \text{oC}\)). We focused on deep hydrotreating of light distillates, which composition was closed to gasoline, over sulfide CoMo/\(\gamma\)-Al\(_2\)O\(_3\) catalyst (Figure 3(a)) and deep hydrotreating of middle distillates, which composition was closed to diesel, over NiMo/\(\gamma\)-Al\(_2\)O\(_3\) catalyst (Figure 3(b)). The results were discussed hereafter.

Deep hydrotreating of light distillates over the sulfide CoMo/\(\gamma\)-Al\(_2\)O\(_3\) catalyst was performed on a stainless-steel batch-type reactor at 350 °C and 7 MPa of H\(_2\) for 5 h (Figure 3(a)). The hydrotreating oil was characterized by GC-FID instrument and elemental analysis. Figure 4 shows that the hydrotreating oil is a gasoline-like fuel, except a small portion of paraffins with carbon number higher than 10. Table 1 shows that the hydrotreated oil contains 29.5 vol.% of \(n\)-paraffins, 14.4 vol.% of \(iso\)-paraffins, 4.5 vol.% of olefins, 21.4 vol. % of naphthene compounds, 29.6 wt.% of aromatic compounds and little amounts of heteroatoms (nearly no oxygen and sulfur, and ca. 50 ppm of nitrogen), corresponding to an octane number of 44. This result suggests that the hydrotreating oil would be suitable for blending with petro-gasoline. On the other hand, the paraffins with
carbon number higher than 10 can be separated from the hydrotreating oil by further distillation, and it would be suitable for use in kerosene [34].

Deep hydrotreating of middle distillates over sulfide NiMo/γ-Al2O3 catalyst was performed by a large-scale batch-type high pressure reactor under the same reaction condition. (Figure 3(b)). In a typical synthesis, a 100 g of middle distillates was mixed with 40 g of sulfide NiMo/γ-Al2O3 catalyst under an atmosphere of H2, followed by heating to 350 °C in 1 hr under pressured atmosphere of H2 (7 MPa) and vigorously stirring. After 350 °C for 5 h, the hydrotreating oil was cooled to ambient condition and corrected by filtration. The yield of hydrotreating oil was 55.2%. The sulfur and nitrogen concentrations of hydrotreating oil were smaller than 10 and 50 ppm, respectively. In Figure 5, the GC analysis equipped with FID and mass detectors indicates that the composition of hydrotreating oil, produced by deep hydrotreating of middle distillates over sulfide NiMo/γ-Al2O3 catalyst, is similar to that of petro-diesel. The distillation curve of hydrotreating oil was analysed by the procedures of JIS K2254 method. The results show that the temperatures for initial distillation, 50 vol% fraction and 95 vol% fraction of hydrotreating oil are 116, 289 and 355 °C, respectively. According to the procedures of JIS K2249 and K2280-5 methods, the density and cetane number of hydrotreating oil are 0.8252 g cm⁻³ and 60.8, respectively. The fuel property of
The sulfide catalysts were prepared by incipient impregnation method. The cobalt- and nickel-promoted molybdenum aqueous solutions (denoted at CoMo(cit) and NiMo(cit), respectively) were freshly prepared by the procedures as described in our previous study [30]. For the preparation of freshly prepared CoMo(cit) and NiMo(cit) aqueous solution, the molybdenum oxide (Wako) was dispersed in hot deionized water (ca. 90 °C) for 12 h under stirring. To this solution, the cobalt nitrate (or nickel nitrate) and citric acid were slowly added under heating and stirring conditions, resulting in freshly prepared CoMo(cit) or NiMo(cit) aqueous solution with molar composition of 1 MoO₃: 0.5 CoO (or NiO): 0.58 C₆H₈O₇: 1.67 H₂O. The extruded γ-Al₂O₃ particle as the supporting materials were dried at 120 °C for 6 h prior to the impregnation. For the preparation of sulfide catalysts, the CoMo(cit) and NiMo(cit) aqueous solutions were
slowly dropped on the extruded $\gamma$-$\text{Al}_2\text{O}_3$ sample under low vacuum (ca. 0.1 torr). The as-made CoMo(cit) and NiMo(cit)-impregnated $\gamma$-$\text{Al}_2\text{O}_3$ samples were aged at the room temperature for 1 h under vacuum, followed by drying through microwave irradiation (1050W, 10Hz) for 10 min. The CoO (or NiO) and MoO$_3$ loadings were 6.1 wt% and 23.6 wt%, respectively. The sulfidation was carried out in a quartz tube reactor using a 5 vol%H$_2$S/H$_2$ standard gas at 360 °C for 6 h. As a result, the sulfide CoMo/Al$_2$O$_3$ and NiMo/Al$_2$O$_3$ catalysts could be prepared. Characterizations were performed by XRD using a Rigaku Miniflex diffractometer, N$_2$ physisorption using a Belsorp instrument and HRTEM determined by a TOPCON EM002B instrument [30].

3.2. Stepwise hydrotreating of Jatropha bio-oil

Jatropha bio-oil produced by thermal pyrolysis of waste Jatropha biomass was kindly supplied by TISTR, Thailand, using a Pilot Plant with a capacity of 20 Kg/h. The elemental and water analyses showed that Jatropha bio-oil contained 3.2 wt% of water and 96.8 wt% of heteroatom-containing hydrocarbon, which composition was 66.5 wt% of carbon, 8.80 wt% of hydrogen and 5.82 wt% of nitrogen and 18.9 wt% of oxygen.

Scheme 1(b) shows a stepwise strategy for upgrading of Jatropha bio-oil over sulfide catalysts under severe conditions. To reduce viscosity and partly deoxygenation, the pre-
treatment of Jatropha bio-oil was performed in a slurry bed reactor using waste sulfide NiMo/γ-Al₂O₃ catalyst (1 wt%) at 400 °C and 7 MPa of H₂ for 2 h. The pre-treated Jatropha bio-oil was distilled and separated into three fractions: (i) light distillates (< 240 °C), (ii) middle distillates (240-360 °C) and (iii) heavy distillates (> 360 °C). The yield of light distillates which composition was closed to gasoline was 21 wt% and that of middle distillates which composition was closed to diesel was around 59 wt%. In this study, we focused on the deep hydrotreating of light and middle distillates over sulfide CoMo/γ-Al₂O₃ or NiMo/γ-Al₂O₃ catalysts into clean and drop-in biofuels (Figure 3). The deep hydrotreating was performed on a high-pressure stainless-steel batch-type reactor at 350 °C and 7 MPa of H₂ for 5 h using a catalyst/oil weight ratio of 0.4. The hydrotreated oils were analysed by Agilent 6890 GC-FID instrument equipped with mass detector, elemental analysis of carbon, nitrogen, hydrogen, sulfur, and the fuel property.

4. Conclusions

Jatropha bio-oil was mostly composed of fatty acids, fatty acid methyl esters, fatty acid amides and derivatives, corresponding to high concentrations of heteroatoms, nitrogen especially. To overcome the catalyst deactivation by those heteroatoms, we had developed a stepwise strategy for hydrotreating of 100 wt% Jatropha bio-oil over sulfide
catalysts to produce clean and drop-in transport biofuels, such as gasoline- and diesel-like biofuels. This stepwise strategy included (i) pre-treatment of Jatropha bio-oil over waste NiMo/γ-Al₂O₃ catalyst (1 wt%) using a slurry-type reactor under severe condition (400 °C, 7 MPa of H₂, 2 h), (ii) distillation of pre-treated Jatropha bio-oil into light distillates (T_d < 240 °C) and middle distillates (T_d = 240-360 °C), (iii) deep hydrotreating of light and middle distillates over sulfide CoMo/γ-Al₂O₃ and NiMo/γ-Al₂O₃ catalysts (40 wt%) using a batch-type reactor under severe condition (350 °C, 7 MPa of H₂, 5 h) to produce clean and drop-in biofuels. Among the step (iii), we found that the hydrotreating oil with gasoline-like composition and an octane number of 44 could be synthesized by deep hydrotreating of light distillates over sulfide CoMo/γ-Al₂O₃ catalyst, and it would be suitable for partly blending with petro-gasoline. On the other hand, the hydrotreating oil with diesel-like composition and a cetane number of 60.8 could be produced by deep hydrotreating of middle distillates over sulfide NiMo/γ-Al₂O₃ catalyst, and it would be suitable for use in diesel engine directly. Moreover, the waste NiMo/γ-Al₂O₃ catalyst could be recycled and used again in the step (i), which reduced the environmental pollution and production cost.

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**Author Contributions:** S.-Y. Chen conceived, designed and performed the experiments; M. Nishi assisted in manuscript editing; T. Mochizuki, H. Takagi, M. Toba, and Y. Yoshimura provided suggestions; S.Y. Chen wrote the paper.

**Conflicts of Interest:** The authors declare no conflict of interest.


24. Laurent, E.; Delmon, B. Study of the hydrodeoxygenation of carbonyl, carboxylic and guaiacyl groups over sulfide CoMo/γ-Al₂O₃ and NiMo/γ-Al₂O₃ catalyst. II. Influence


Table 1. The elemental analysis, composition and octane number of gasoline-like fuel.\textsuperscript{a}

<table>
<thead>
<tr>
<th>Sulfur (ppm)</th>
<th>Nitrogen (ppm)</th>
<th>Octane number</th>
<th>H/C</th>
<th>Density (g/cm\textsuperscript{3})</th>
<th>n-Paraffin (vol%)</th>
<th>\textit{iso}-Paraffin (vol%)</th>
<th>Olefin (vol%)</th>
<th>Naphthene (vol%)</th>
<th>Aromatic (vol%)</th>
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<td>1.77</td>
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<td>14.4</td>
<td>4.99</td>
<td>21.4</td>
<td>29.6</td>
</tr>
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\textsuperscript{a} Synthesized by stepwise hydrogenation of Jatropha bio-oil over sulfide CoMo/\(\gamma\)-Al\(_2\)O\(_3\) catalysts. The reaction condition for deep hydrogenation (Scheme 1(b) and Figure 3(a)): 350 °C, 5 h, 2 g of sulfided CoMo/\(\gamma\)-Al\(_2\)O\(_3\) catalyst, 5 g of light distillate obtained by distillation of pre-treated Jatropha bio-oil at the temperature lower than 240 °C.
Figure 1. (A) powered XRD patterns and (B) N$_2$ adsorption-desorption isotherms of mesoporous sulfide catalysts: (b) CoMo/$\gamma$-Al$_2$O$_3$ and (c) NiMo/$\gamma$-Al$_2$O$_3$ catalysts, in comparison to those of a supporting material: (a) $\gamma$-Al$_2$O$_3$. The asterisk and gamma ($\gamma$) represent the characteristic peaks of Co-incorporated MoS$_2$-like slabs (or Ni-incorporated counterpart) and gamma-alumina framework, respectively.
Figure 2. HRTEM images of mesoporous sulfide catalysts: (a) CoMo/γ-Al₂O₃ and (b) NiMo/γ-Al₂O₃.
Figure 3. Stepwise hydrotreating of Jatropha bio-oil over sulfide catalysts to produce gasoline-like and diesel-like fuels.
Figure 4. GC-FID profiles of gasoline and hydrotreating oil, which is produced by deep hydrotreating of light distillates over sulfide CoMo/γ-Al₂O₃ catalyst at 350 °C and 7 MPa of H₂ for 5 h.
Figure 5. GC profiles of diesel and hydrotreating oil, which is produced by deep hydrotreating of middle distillates over sulfide NiMo/γ-Al₂O₃ catalyst at 350 °C and 7 MPa of H₂ for 5 h.
Figure 6. Distillation curve of hydrotreating oil, which is produced by deep hydrotreating of middle distillates over sulfide NiMo/γ-Al2O3 catalyst at 350 °C and 7 MPa of H2 for 5 h.