

Investigation of Nickel as a Metal Substitute of Palladium Supported on HBeta Zeolite for Waste Tire Pyrolysis

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Abstract—Pyrolysis of waste tire is one of alternative technique to produce petrochemicals, such as light olefins, mixed C₄, and mono-aromatics. Noble metals supported on acid zeolite catalysts were reported as potential catalysts to produce the high valuable products from waste tire pyrolysis. Especially, Pd supported on HBeta gave a high yield of olefins, mixed C₄, and mono-aromatics. Due to the high prices of noble metals, the objective of this work was to investigate whether or not a non-noble Ni metal can be used as a substitute of a noble metal, Pd, supported on HBeta as a catalyst for waste tire pyrolysis. Ni metal was selected in this work because Ni has high activity in cracking, isomerization, hydrogenation and the ring opening of hydrocarbons. Moreover, Ni is an element in the same group as Pd noble metal, which is VIII B group, aiming to produce high valuable products similarly obtained from Pd. The amount of Ni was varied as 5, 10, and 20% by weight, for comparison with a fixed 1 wt% Pd, using incipient wetness impregnation. The results showed that as a petrochemical-producing catalyst, 10%Ni/HBeta performed better than 1%Pd/HBeta because it did not only produce the highest yield of olefins and cooking gases, but the yields were also higher than 1%Pd/HBeta. 5%Ni/HBeta can be used as a substitute of 1%Pd/HBeta for similar crude production because its crude contains the similar amounts of naphtha and saturated HCs, although it gave no concentration of light mono-aromatics (C₆-C₁₁) in the oil. Additionally, 10%Ni/HBeta that gave high olefins and cooking gases was found to give a fairly high concentration of the light mono-aromatics in the oil.

Keywords—Catalytic pyrolysis; Waste tire; Pd; Ni; HBeta

I. INTRODUCTION

NOWADAYS, with the increase in the petroleum fuel consumption and the inadequate of conventional fuel, fuels from wastes or alternative fuels are used for substituting petroleum-based fuels. The fuels from wastes can be produced by several sources such as wood, tar sand bitumen, biomass, and especially from waste tires. Because the structure of tire is designed to struggle to degradation, the production of fuels from waste tires becomes interesting. Moreover, a large quantity of waste tires is generated in the world due to the evolution of vehicle technology, which has been causing serious environmental problems. Pyrolysis of waste tires is a suitable option since it does not only produce petroleum-based fuel substitutes, but also solves the environmental crisis.

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Pyrolysis is the thermal degradation process of the tire under the oxygen-free condition.

The pyrolysis products of waste tire can be categorized into three phases at room temperature, i.e., gas product, liquid oil, and solid residue (char or ash) [1]. The tire pyrolysis oil has a high calorific value of around 41-44 MJ kg⁻¹[2]. Thus, it can be used as replacements for conventional fuels, and char can be also useful either as a smokeless fuel, carbon black, or activated charcoal [3]. The pyrolysis technique can crack the high molecular weight of rubber and other organic compounds in waste tires. The variety of high value products are obtained such as olefins (ethylene and propylene) cooking gases, mixed C₄, and mono-aromatics (benzene, toluene and xylenes) and etc. Moreover, sulfur elements, which were used for crosslinking the polymer chains of rubber [4], are also cracked in the pyrolysis process. Through pyrolysis, sulfur atoms are present as polar-aromatics in the tire-derived oil. Many researchers reported that the bifunctional catalysts were used for reducing polar-aromatic compounds in the heavy gas oil and gasoline ranges [5]. As well known, the hydrogenation functionality of noble metals makes them the potential catalysts for deep HDS via the hydrogenation (HYD) pathways [6]. In addition, noble metals supported on an acidic support can increase the activity on hydrogenation of aromatic compounds, and improve the deep hydrodesulfurization [7]-[9].

From a previous work, noble metals were used to optimize the high value products from the pyrolysis of waste tires, especially mono-aromatics. The mono-aromatics such as benzene, toluene, and xylenes are very versatile chemical feedstocks used to produce many commercial products. Noble metals supported on acid zeolite catalysts, especially Pd supported on HBeta were reported as potential catalysts to produce the high valuable products as olefins, mixed C₄, and mono-aromatics from waste tire pyrolysis [10]. In case of non-noble metals, Ni is an active catalyst for several industrial processes. Ni catalysts have been used in hydrotreating, and hydroisomerization process [11]. Due to the high prices of noble metal catalysts, the objective of this research was to use non-noble Ni metal as a substitute of Pd metal catalysts. Ni supported on HBeta zeolite catalyst was used in this research because Ni catalysts have high activity in cracking, isomerization, hydrogenation and the ring opening of hydrocarbons[12]-[13]. Moreover, Ni is elements in the same group as Pd noble metals, which are VIII B group, aiming to produce high valuable products similar to the noble metals.

II. EXPERIMENTAL

A. Catalyst Preparation

The catalysts prepared based on Beta zeolite supplied by Tosoh Company (Singapore) was calcined at 600°C for 5 hrs with the heating rate of 2°C/min. The Pd and Ni catalysts were prepared by impregnating the zeolites support with a precursor aqueous solution of palladium (II) nitratedihydrate ($\text{Pd}(\text{NO}_3)_2 \cdot 2\text{H}_2\text{O}$) and nickel nitrate hexahydrate ($\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$), respectively.

The amount of Pd loading was fixed to 1%, and that of Ni was varied at 5, 10, and 20% by weight. Then, the samples were dried in an oven at 110°C for 3 hours followed by calcination in a furnace at 500°C for 3 hours with the heating rate of 5°C/min. Before the catalysts were used in the pyrolysis reactor, they were pressed to pellets using a hydraulic pelletizer. Then, the pellets were crushed and sieved into the particle size between 400 and 425 μm using the mesh size between 40 and 60 of sieves. Finally, the catalysts were reduced for 2 hours with H_2 in order to convert the metal oxide forms to metal elements.

B. Pyrolysis of Waste Tire

The diagram of experimental setup for waste tire pyrolysis process is shown in Figure 1. The waste passenger car tire (Bridgestone TURUNZA GR-80) was scraped by a grinder, and sieved to obtain a particle size range of 8-18 mesh. First, the scraped waste tire was loaded into the pyrolysis zone (the lower zone), and the prepared catalyst was loaded into the catalytic zone (the upper zone). The reactor was heated by a furnace from room temperature to a final temperature with the heating rate 10°C/min. The catalytic final temperature was 300°C, and the pyrolysis final temperature was 500°C. The evolved product was transported by nitrogen to an ice bath condenser system containing two condensers in order to separate non-condensable compounds from the liquid product. Non-condensable products or gaseous products were passed through the condensers to a gas sampling bag. The non-condensable gas product was analyzed by using a Gas Chromatography, Agilent Technologies 6890 Network GC system, using HP-PLOT Q column: 30 m x 0.32 mm ID and 20 μm film thicknesses. A detector was a FID type using He as the carrier gas.

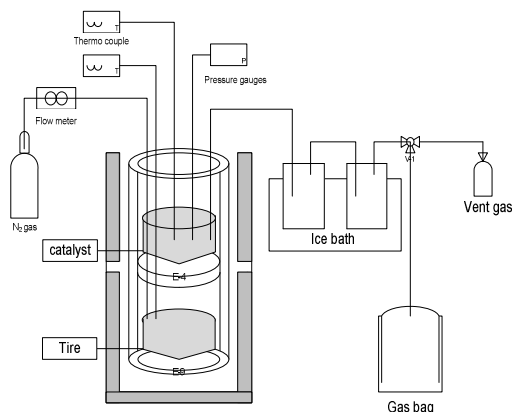


Fig. 1 Schematic experimental system of waste tire pyrolysis

Oil products were mixed with n-pentane at the ratio of 40:1, and the solution were shaken for 15 min in an ultrasonic bath. It was left overnight to precipitate asphaltene, after that asphaltene was filtrated by using a 0.45 μm Teflon membrane in a vacuum system. The solution after filtration was evaporated by a rotary vacuum evaporator in 37 °C in order to remove n-pentane and obtain maltene solution. Maltene solution was extracted to each functional group as shown in Table I by using a liquid chromatography column (650 height x 26.6 mm. I.D.) packed with alumina in the bottom and silica gel on the top.

The column was immersed with n-hexane for overnight. The extraction was started with adding a mobile phase as shown in Table I. The flow rate of the mobile phase was kept constant at 20 cm^3/min controlled by an aquarium air pump. Then, the mobile phase was evaporated from each functional group by a rotary vacuum evaporator at about 60°C [14].

All functional groups (saturated hydrocarbons, mono-aromatics, di-aromatics, poly-aromatics, and polar-aromatics) obtained from the liquid chromatography were analyzed for the true boiling point curves using a Varian GC-3800 simulated distillation gas chromatograph (SIMDIST-GC). The liquid samples were injected to the SIMDIST GC after dilution in carbon disulphide (CS_2).

TABLE I
COMPOSITIONS AND VOLUMES OF MOBILE PHASES FOR THE
CHROMATOGRAPHIC COLUMN [14]

Mobile phase	Volume (cm^3)	Compounds type
Hexane	600	Saturated hydrocarbons
Hexane-benzene (24:1, v/v)	500	Mono-aromatics
Hexane-benzene (22:3, v/v)	500	Di-aromatics
Benzene	500	Poly-aromatics
Benzene-diethylether-methanol (1:1:3 v/v)	500	Polar-aromatic compounds

III. RESULTS AND DISCUSSION

A. Gas to liquid ratio

The product obtained from waste tire pyrolysis consists of gas, liquid, and solid residue (char). The products obtained from catalytic pyrolysis of waste tire using Pd and Ni supported on HBeta zeolites are compared and discussed quantitatively and qualitatively. The product distributions obtained from waste tire pyrolysis can be explained by plotting the gas to liquid ratio as shown in Fig.2. The results show that, 1%Pd/HBeta as the reference gives a higher the G/L ratio than the non-catalytic case (thermal pyrolysis) and pure HBeta zeolite. Namely, its G/L ratio is 0.6, which is greater than 0.4 (the catalytic case) and 0.55 (pure HBeta case). The increment of G/L ratio suggests that the gas product increases with the decrease in the liquid product, indicating higher cracking activity of a catalyst. This result is attributed to the reason that heavy molecules can be cracked into lighter molecules on the metal and acid sites of Pd/HBeta.

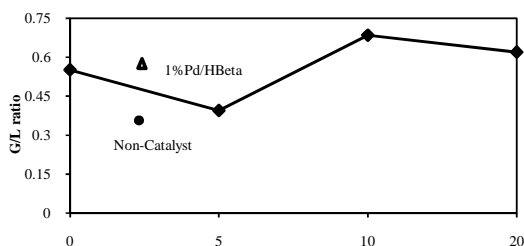


Fig. 2 G/L ratio obtained from using various % Ni/HBeta in comparison with (●) Non-catalytic and (Δ) 1%Pd/HBeta cases

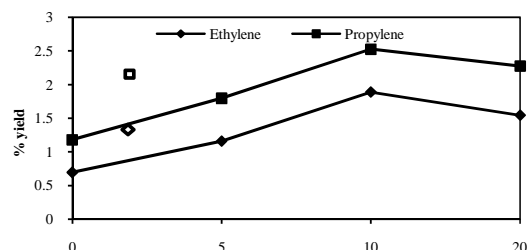


Fig. 3 Yield of ethylene and propylene obtained from using various % Ni/HBeta in comparison with: (◇) ethylene and (□) propylene yields from 1%Pd/HBeta

The presence of all Ni/HBeta catalysts increases the G/L ratio from that of the non-catalytic case, especially 10%Ni/HBeta that gives the highest G/L ratio. The high amounts of Ni (10% and 20%) produce the higher G/L ratios than the non-catalytic and reference cases. The result indicates the high amounts of Ni increase the cracking activity. In addition, 20%Ni/HBeta gives the closest G/L ratio to that of 1%Pd/HBeta.

B. Petrochemicals

The non-condensable gases obtained from pyrolysis contain high value petrochemicals such as olefins (ethylene and propylene), cooking gases (hereby presented in terms of propane and mixed C₄), and mixed C₄. The comparisons on the yields of petrochemicals obtained from Ni-loaded catalysts and 1%Pd/HBeta are shown in Fig. 3-5.

1. Yield of Olefins

For the reference, 1%Pd/HBeta gives higher yields of ethylene and propylene than that of pure HBeta zeolite, which are about 1.4% and 2.2% respectively. Fig. 3 shows that when the percentage of Ni loading increases, the yields of ethylene and propylene increase in the same trend. Moreover, the Ni catalysts, except at 5%Ni loading, give a higher yield of light olefins than that of pure HBeta zeolite. In addition, 10%Ni/HBeta exhibits the highest yield of light olefins, which are subsequently slightly decreased when the loading increases to 20%Ni. Nevertheless, 20%Ni/HBeta exhibits the yield of light olefins close to that of 1%Pd/HBeta. From this figure, it can be seen that 10%Ni/HBeta gives the higher yield of light olefins than that 1%Pd/HBeta.

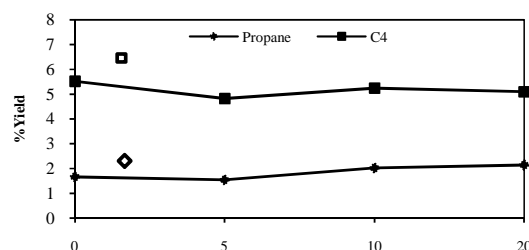


Fig. 4 Yield of cooking gases obtained from using various %Ni/HBeta in comparison with: (◇) propane and (□) C₄ yields from 1%Pd/HBeta

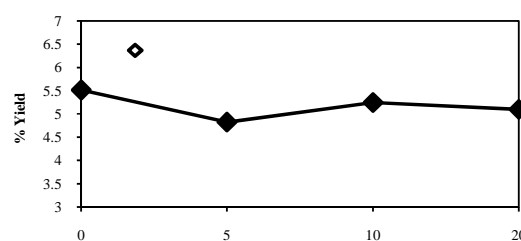


Fig. 5 Yield of mixed C₄ obtained from using various %Ni/HBeta zeolite in comparison with: (◇) Mixed C₄ yield from 1%Pd/HBeta

2. Yield of Cooking gases

The yield of cooking gases (propane and mixed C₄) also increases with Ni loading in the similar trend as the yield of olefins, especially propane. As shown in Fig. 4, 1%Pd/HBeta gives 2.2wt% and 6.5wt% yields of propane and mixed C₄, respectively, which are higher than that of pure HBeta. It is also exhibited that the yield of propane slightly increases whereas the yield of mixed C₄ insignificantly increases with the increased percentage of Ni loading. In case of the propane, the all Ni catalysts show the higher yield of propane than that of pure HBeta zeolite and 20%Ni/HBeta gives the similar yield of propane as 1%Pd/HBeta. Moreover, 10%Ni/HBeta does not only produce the highest yield of light olefins, but also produces the high yields of cooking gases.

3. Yield of Mixed C₄

One of high economic value gases is mixed C₄, which is one of the predominant gas products obtained from the pyrolysis of scrap tire. For the reference, 1%Pd/HBeta produces 6.5% yield of mixed C₄. As can be seen in Fig. 5, as the percentage of Ni loading increases, the yield of mixed C₄ is constant at about 5% for all Ni-loaded catalysts. It can be concluded that Ni catalyst cannot be used as a suitable catalyst as a substitute of 1%Pd/HBeta for mixed C₄ production. As shown in Fig 2-5, the results exhibit that 10%Ni/HBeta seems to be a potential catalyst to produce light olefins and cooking gases. At the higher loading (20%Ni/HBeta), the yields of light olefins and cooking gases slightly decrease. Nonetheless, 20%Ni/HBeta gives the closest yields of light olefins and propane as 1%Pd/HBeta. For a high amount of Ni loading, the agglomeration of Ni can reduce dispersion and active sites. Furthermore, Eswaramoorthi *et al.*, 2003[15] studied the Ni loaded on zeolite-β by incipient wetness impregnation (IWI) for the hydroisomerisation of *n*-heptane. They reported when the amount of Ni increases, the total acidity of catalyst conti-

nously falls by reasons of the acid sites covered by Ni species.

C. Maltene Composition

The chemical compositions of maltenes obtained from using varied loading percentages of Ni/HBeta catalysts as compared to pure HBeta and 1%Pd/HBeta are shown in Fig. 6.

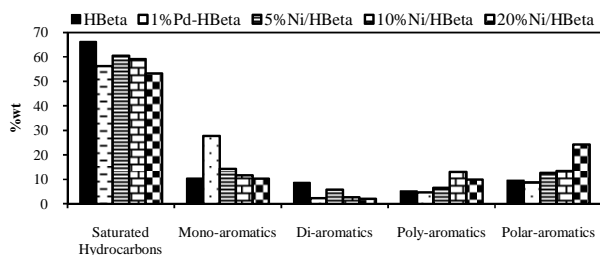


Fig. 6 Chemical compositions in maltenes obtained from using varied Ni/HBeta catalysts in comparison with that from 1%Pd/HBeta

HBeta zeolite produces the highest concentration of saturated hydrocarbons of about 66.2wt%, whereas 1%Pd/HBeta gives the lower concentrations of saturated hydrocarbons of 56.3wt% in the pyrolytic oil. When the percentage of Ni loading increases, the concentration of saturated hydrocarbons slightly decreases. 5%Ni/HBeta and 10%Ni/HBeta give a higher concentration of saturated hydrocarbons than 1%Pd/HBeta. The results show that 1%Pd/HBeta dramatically increases the mono-aromatics concentrations from 10wt% to 27.8wt% when compared to pure HBeta zeolite. On the other hand, the concentration of mono-aromatics is lower with using the Ni-loading catalysts. However, it is still higher than that of pure HBeta, but lower than that of 1%Pd/HBeta. Moreover, the concentrations of poly- and polar-aromatics rapidly increase when all Ni-loaded catalysts are used. It can be suggested that a higher cracking activity catalyst produces a higher concentration of poly-aromatics because the high cracking ability can generate carbocations which are intermediates to form aromatic compounds [6]. 1%Pd/HBeta produces a high quality of oil products with a high concentration of saturated hydrocarbons and low concentrations of poly- and polar-aromatics. The Ni-loaded catalyst at a high Ni loading cannot be used as a substitute of 1%Pd/HBeta for the good quality of oil production because it gives the high concentrations of poly- and polar-aromatics.

D. Petroleum Fractions

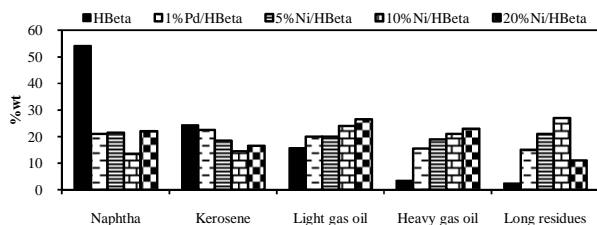


Fig. 7 Petroleum fractions in maltenes obtained from using varied %loading of Ni/HBeta catalysts in comparison with that of 1%Pd/HBeta

The maltenes were analyzed by a SIMDIST-GC for the true boiling point curves, and then cut to petroleum fractions, which are naphtha (<200 °C), kerosene (200–250 °C), light gas oil (250–300 °C), heavy gas oil (300–370 °C), and long residue (>370 °C)

Fig. 7 shows the petroleum fractions of maltenes obtained from using varied percentages of Ni loading on HBeta zeolite as compared with 1%Pd/HBeta. It can be clearly seen that pure HBeta give the highest concentration of naphtha and kerosene. The result indicates that pure HBeta produces the lighter oil fraction than that of other catalysts. 1%Pd/HBeta gives the higher concentration of kerosene than that of all Ni/HBeta catalysts. All Ni/HBeta catalysts give the similar concentration of naphtha as that of 1%Pd/HBeta, except 10%Ni/HBeta. The high amount of Ni loaded catalyst produces the higher concentration of light and heavy gas oil. Additionally, the high amount of Ni loading produces the lower concentration of kerosene than that of 1%Pd/HBeta. Moreover, 10%Ni/HBeta produced high poly-aromatics. It can be suggested that 10%Ni/HBeta produces the heaviest oils than the other catalysts. It can be generally concluded that the addition of Ni produces the same amount of naphtha, but the greater in gas oils and long residue in the expense of kerosene reduction. The 5%Ni/HBeta can be used as a substitute of 1%Pd/HBeta for similar crude oil production.

E. Average carbon number of mono-aromatics.

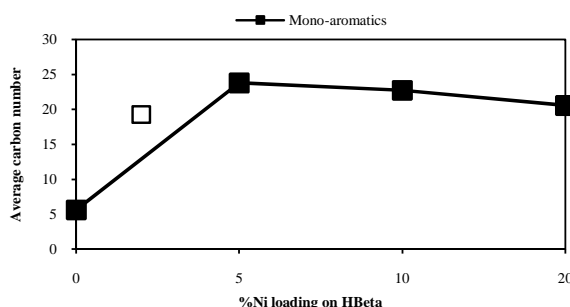


Fig. 8 Average carbon number of mono-aromatics fractions obtained from using various % Ni/HBeta in comparison with (□) 1%Pd/HBeta

Fig.8 illustrates the average carbon number of mono-aromatics in obtained from using varied loading percentages of Ni/HBeta catalysts as compared to that of 1%Pd/HBeta.

From this figure, the average carbon number of mono-aromatics slightly decreases with the increased percentage of Ni loading. This result is attributed to the reason that the high Ni loading exhibits hydrogenation and ring-opening activity on Ni metal sites. Moreover, pure HBeta gives the lowest of average carbon number of mono-aromatics. Therefore, it can be concluded that Ni loading helps improving the production of short chain mono-aromatics via the ring-opening of di-aromatics. Additionally, 20%Ni/HBeta gives the similar average carbon number of mono-aromatics as that of 1%Pd/HBeta.

In mono-aromatic portion, 10%Ni/HBeta, however, produces the considerably-high concentration of light mono-aromatics (C₆-C₁₁) as shown in Table II. Additionally, the concentration of light mono-aromatics from 10%Ni/HBeta is as much as a half of those obtained from 1%Pd/HBeta.

5%Ni/HBeta and 20%Ni/HBeta rarely produce light mono-aromatics (C₆-C₁₁). The aromatic compounds can be produced via Diels-Alders reactions of olefins obtained from primary cracking reactions and/or the ring-opening of di-aromatics.

TABLE II
CONCENTRATION OF LIGHT MONO-AROMATICS (% wt)

Carbon No.	1%Pd/ HBeta	5%Ni/ HBeta	10%Ni/ HBeta	20%Ni/ HBeta
C ₆ -C ₈ (BTX)	4.51	0	1.80	0
C ₉	2.16	0	1.01	0.001
C ₁₀	2.54	0	1.28	0.023
C ₁₁	2.94	0.002	1.59	0.267

F. Comparison of catalyst prices

Since palladium is a noble metal that has a very high price, nickel as an element in the same group (VIII B group) that may be used as a substitute of palladium. Moreover, nickel is a non-noble metal which has a low price. As shown previously, in the case of gaseous products, 10%Ni/HBeta exhibits a good catalyst for light olefins and cooking gases production which produced the yields as high as that of 1%Pd/HBeta. Moreover, 10%Ni/HBeta produces the high valuable mono-aromatics (BTX) as much as a half of that those obtained from 1%Pd/HBeta. According to these results, 10%Ni/HBeta catalyst may be used as a substitute of 1%Pd/HBeta to produce highly valuable gas and mono-aromatics products.

Table III shows the comparison of precursor prices. The precursor of Pd (Palladium (II) nitrate dihydrate) is more expensive than that of the non-noble metal (Nickel nitrate hexahydrate). As shown in Table III, if 10%Ni/HBeta is used as a substitute of 1%Pd/HBeta, the cost of catalyst is reduced by 9 times.

TABLE III
PRECURSOR PRICES

Metal	Precursor	Price (Baht)/g	%loaded (%wt)	Price (Baht)
Pd	Palladium(II)nitratetdihydrate (Pd(NO ₃) ₂ ·2H ₂ O)	2,600 ^a	1%	658
Ni	Nickel nitrate hexahydrate (Ni(NO ₃) ₂ ·6H ₂ O)	13.8 ^b	10%	75.9

^a Sigma-Aldrich in 2011

^b Merck in 2011

IV. CONCLUSIONS

Since palladium is a noble metal that has very high price, nickel was expected to substitute the palladium metal because it is an element in the same group as palladium in the periodic table. Moreover, nickel does not only has low price, but it is also a high potential catalyst. As shown previously, the 10%Ni/HBeta gave the same yield of light olefins and cooking gas and a half of light mono-aromatics yield of that from 1%Pd/HBeta. The 10%Ni/HBeta catalyst can be used as a substitute of 1%Pd/HBeta catalyst for the production of high valuable gases and light mono-aromatics, whereas, 5%Ni/HBeta was found to be a good substitute of 1%Pd/HBeta for the production of similar oil.

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REFERENCES

- Chang, Y.M., (1996). On pyrolysis of waste tire: degradation rate and product yields. Resources, Conservation and Recycling, 17, 125-139
- Díez, C., Martínez, O., Calvo, L.F., Cara, J., and Morán, A., (2004). Pyrolysis of tyres. Influence of the final temperature of the process on emissions and the calorific value of the products recovered. Waste Management, 24, 463-469
- Williams, P.T. and Taylor, D.T., (1993). Aromatization of type pyrolysis oil to yield polycyclic aromatic hydrocarbons. Fuel, 72, 1469-1474
- Williams, P.T., Serpil Besler., and Taylor, D.T., (1990). The pyrolysis of scrap automotive tyres. The influence of temperature and heating rate on product composition. Fuel, 69, 1474-1482
- Düng, N.A., Tanglumlert, W., and Jitkarnka, S., (2008). Effects of pyrolysis temperature and Pt-loaded catalysts on polar-aromatic content in tire-derived oil. Applied Catalysis B: Environmental, 91, 300-307
- Ishihara, A., Dumeignil, F., Lee, J., Mitsuhashi, K., Qian, E.W., and Kabe, T., (2005). Hydrodesulfurization of sulfur-containing polyaromatic compounds in light gas oil using noble metal catalysts. Applied Catalysis A: General, 289, 163-173
- Tang, T., Yin, C., Wang, L., Ji, Y., and Xiao, F-S., (2008). Good sulfur tolerance of a mesoporous Beta zeolite-supported palladium catalyst in the deep hydrogenation of aromatics: Journal of catalysis, 257, 125-133
- Loiha, S., Föttinger, K., Zorn, K., Klysubun, W., Rupprechter, G., and Wittayakun, J., (2009). Catalytic enhancement of platinum supported on zeolite beta for toluene hydrogenation by addition of palladium. Journal of Industrial and Engineering Chemistry, 15, 819-823
- Castaño, P., Pawelec, B., Fierro, J.L.G., Arandes, J.M., and Bilbal, J., (2007). Enhancement of pyrolysis gasoline hydrogenation over Pd-promoted Ni/SiO₂-Al₂O₃ catalysts: Fuel, 86, 2264-2274
- Choosuton, A., (2007). Development of Waste Tire Pyrolysis for the Production of Commercial Fuels: Effect of Noble Metals and Supports. M.S. Thesis, The Petroleum and Petrochemical College, Chulalongkorn University, Bangkok, Thailand.
- Fúnez, A., Lucas, A.D., Sánchez, P., Ramos, M.J., and Valverde, J.L., (2008) Hydroisomerization in liquid phase of a refinery naphtha stream over Pt-Ni/H-beta zeolite catalysts. Chemical Engineering Journal, 136, 267-275
- Cañizares, P., De Lucas, A., Dorado, F., Durán, and A., Asencio, I., (1998) Characterization of Ni and Pd supported on H-mordenite catalysts: Influence of the metal loading method. Applied Catalysis A: General 169, 137-150
- Jao, R.M, Lin, T.B, and Chang, J.R., (1996) Light Naphtha Isomerization over Mordenite-Supported Ni-Pt Catalysts: Effects of Ni on the Catalytic Performance for Pure Feed and Sulfur-Containing Feed JOURNAL OF CATALYSIS 161, 222-229 (1996).
- Sebor, G., Blazek, J., and Nemer, M.F., (1999) Optimization of the preparative separation of petroleum maltenes by liquid adsorption chromatography. Journal of Chromatography A, 847, 323-330.
- Eswaramoorthi, L., Bhavani, A.G., and Lingappan, N., (2003). Activity, selectivity and stability of Ni-Pt loaded zeolite-β and mordenite catalysts for hydroisomerisation of n-heptane. Applied Catalysis A: General, 253, 469-486