

Energy Engineering and Management



George Thomson

Energy Engineering and Management

About the Book

Energy engineering and energy management are two vast interrelated areas of study. While energy engineering deals with aspects such as alternative energy, energy efficiency, etc.; energy management on the other hand is concerned with the consumption, conservation as well as production of energy. This book elucidates the concepts and innovative models around prospective developments with respect to energy engineering and management. It presents researches and studies performed by experts across the globe. In this book, using case studies and examples, constant effort has been made to make the understanding of the difficult concepts of these fields as informative as possible, for the readers.

About the Editor

George Thomson received his master's degree in renewable energy from University of Exeter, United Kingdom. He specializes in the fields of bioenergy and geothermal energy; and has contributed towards research of the same. Thomson has produced several articles and books focused on energy conservation and related environmental concerns. He has been an eminent speaker in seminars across Europe, United States, Canada and Middle Asia. His thorough efforts towards addressing environmental issues have been recognized and appreciated globally.

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PREFACE

Energy engineering and energy management are two vast interrelated areas of study. While energy engineering deals with aspects such as alternative engineering, energy efficiency, etc.; energy management on the other hand is concerned with the consumption, conservation as well as production of energy. This book elucidates the concepts and innovative models around prospective developments with respect to energy engineering and management. It presents researches and studies performed by experts across the globe. In this book, using case studies and examples, constant effort has been made to make the understanding of the difficult concepts of these fields as informative as possible, for the readers.

This book is a comprehensive compilation of works of different researchers from varied parts of the world. It includes valuable experiences of the researchers with the sole objective of providing the readers (learners) with a proper knowledge of the concerned field. This book will be beneficial in evoking inspiration and enhancing the knowledge of the interested readers.

In the end, I would like to extend my heartiest thanks to the authors who worked with great determination on their chapters. I also appreciate the publisher's support in the course of the book. I would also like to deeply acknowledge my family who stood by me as a source of inspiration during the project.

Editor

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Hydrotreating reactions of tall oils over commercial NiMo catalyst

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Commercial NiMo catalyst, decarboxylation, hydrogenation, hydrotreating, tall oil

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Abstract

Catalytic hydrotreating is an attractive method for upgrading bio-derived oils into renewable feedstocks with less oxygen content, suitable for producing valuable hydrocarbons through various petro-refinery processes. This study evaluates the catalytic activity of a commercial alumina (Al₂O₃) supported NiMo catalyst for hydrotreating tall oil feeds such as crude tall oil (CTO), distilled tall oil (DTO), and tall oil fatty acid (TOFA). Catalytic experiments carried out in a bench-scale fixed bed reactor set-up at different process conditions [space velocity (1–3 h⁻¹), temperature (325–450°C), and H₂ pressure (5 MPa)] produced a wide-range of products from tall oil feeds. Hydrotreating of TOFA produced highest yield of *n*-alkanes (>80 wt%) compared to DTO and CTO hydrotreating. A high conversion of fatty acids and resin acids was obtained in DTO hydrotreating. In CTO hydrotreating, a drop in conversion of fatty acids and resin acids was observed especially at the lowest temperature tested (325°C). The study revealed that there are various deoxygenation pathways preferential at different hydrotreating temperatures. As an example for TOFA, the decarboxylation route is dominant over the hydrodeoxygenation route at high temperatures (>400°C).

Introduction

Catalytic hydrotreating is an essential petro-refinery method to reduce the content of heteroatoms (S, N, and O) from raw materials, which has been widely employed to upgrade refinery feeds prior to such processes as catalytic reforming, catalytic cracking, and steam cracking [1]. In petro-refineries that use sulfur-rich fossil-fuel-based feeds, the catalytic hydrotreating technology is fully developed specifically for the hydrodesulfurization (HDS) of petroleum products and naphtha streams [2–4]. However, the recent research developments prompted by the increasing demand of bio-based fuels and chemicals reinvent the importance of developing optimal hydrotreating (hydrodeoxygenation, HDO) methods for reducing the

amount of oxygenates from complex bio-derived feeds before the thermochemical conversion process into fuels or chemicals.

The amount of oxygenates in bio-derived oils vary depending on the origin of raw materials. Bio-oils produced by pyrolysis of lignocellulosic biomass are rich in oxygenates (35–40%). Therefore, deep hydrotreatment conditions are required to achieve complete deoxygenation from such bio-oils, inducing high processing cost [5]. Plant-based oils or vegetable oils are another class of bio-derived feedstock. Vegetable oils have been extensively studied as a feedstock for the production of bio-chemicals and biofuels through a catalytic HDO route [6–9]. The patented bio-synfining process produces naphtha range hydrocarbons for conventional steam cracking process

from vegetable oils and fats [10, 11]. However, most of the widely studied vegetable oils are edible and remain as less favorable feedstocks as their selection to a refinery may create several environmental, economic, and societal issues. Therefore, a proper selection of a sustainable feedstock is vital. Tall oil, a by-product of the Kraft-pulping process, is nonfood chain affecting, economically feasible and low oxygen content feedstock [12]. Tall oil upgrading has already been received substantial attention as a sustainable bio-refinery method for producing biofuels and refinery feeds [12–14]. Tall oil comprises fatty acids, resin acids, and sterols. Different tall oil feeds such as crude tall oil (CTO), distilled tall oil (DTO), and tall oil fatty acid (TOFA) are commercially available, and can be used as valuable raw materials for chemical production. CTO is produced by means of the acidulation of tall oil soap skimmings from the black liquor which is obtained from pulping. DTO and TOFA are obtained from CTO distillation along with other fractions. Among the aforementioned tall oil feeds, CTO is regarded as the most cost-competitive raw material [15].

Sulfided molybdenum catalysts on alumina supports with nickel or cobalt as promoter metals are the most widely employed industrial catalysts for hydrotreating [16]. Supported CoMo and NiMo catalysts are more active in sulfided forms. There have been many studies reported on the origin of catalytic synergy between two main group elements in hydrotreating catalysts [17]. Different theories on the origin of catalytic activity and the nature of active sites can be found in literature [17, 18]. Kubicka et al. [19] reports that during hydroprocessing of vegetable oils over a sulfided NiMo catalyst, nickel sulfide phases are more active for decarboxylation than molybdenum sulfide phases. Therefore, the extent of HDO (hydrogenation/dehydration) versus decarboxylation reactions is highly dependent on factors such as promoter metal (Ni) concentrations and the dispersion of sulfidic phases. It is already learnt from previous studies that in comparison with CoMo catalysts, NiMo catalysts are more active for the HDO of aliphatic oxygenates [20]. Moreover, NiMo catalysts are found to be effective for hydrodeoxygenating cyclic oxygenates to cycloalkanes and also for causing ring opening reactions from cyclics at high temperatures, which produces valuable hydrocarbons for further refinery processes [12, 21]. Based on these observations, it can be suggested that NiMo catalyst is more applicable than a CoMo catalyst for hydrodeoxygenating bio-derived oils such as tall oil which contains aliphatic oxygenates as well as cyclic oxygenates. During catalytic hydrotreating of tall oil, oxygenates are removed by various deoxygenation routes which produces a wide range of hydrocarbons mainly paraffin range hydrocarbons [22, 23].

Among tall oil fractions, catalytic deoxygenation of TOFA has been studied with considerable interest for producing a hydrocarbon fraction suitable as a diesel fuel [24]. Egeberg et al. [2] reports that hydroconversion of TOFA can be slightly different than that of triglycerides (vegetable oils) as the former produces more methane by means of methanation reaction, whereas the latter produce more propane by the scission of glycerol backbone. Catalytic deoxygenation of TOFA investigated by other researchers reveal that a significant yield of *n*-heptadecane (C_{17}) with high selectivity can be obtained from TOFA using a palladium mesoporous carbon catalyst [24]. Low temperatures are found to be more favorable for the formation of *n*-octadecane from fatty acids through a HDO route. Hydrotreating of CTO has been discussed in the literature through several patents which mainly focuses the application of hydrotreated products as a diesel fuel [25–27]. Previously, we successfully reported on the use of hydrotreated DTO and CTO as a steam cracker feed [22, 23]. A high degree of deoxygenation was obtained at low temperatures (325–400°C) and space velocity of weight hourly space velocity (WHSV) = 1 h⁻¹, yielding a maximum in paraffins. Our group has also studied the hydrotreating chemistry of sterols in CTO and proposed a reaction scheme for the HDO of sterols at low temperatures in line with studies on the HDO of phenolic compounds and saturated alicyclic alcohols over sulfided catalysts [23]. Importantly, in our study, a high conversion of sterols was obtained at the tested conditions irrespective of space time and temperature.

In this study, a comparative study is presented using different tall oil feedstocks (TOFA, DTO, and CTO). The effect of space time and temperature on the hydrotreating of DTO and CTO is already been reported [22, 23], therefore, they are not discussed further in this study. More specifically, this study presents the results of TOFA hydrotreating under the applied conditions, which are then compared with the results of DTO and CTO hydrotreating. This comparison has carried out on the basis of achieved product distribution, composition of organic phase samples and the conversion of acid fractions at the most favorable space time (WHSV = 1 h⁻¹). The influence of feedstock type and reaction severity (temperature) during hydrotreating of tall oils (6 h of time on stream) over a sulfided NiMo catalyst is thus studied in this article.

Materials and Methods

Commercially available TOFA (SYLFAT[®] 2) and DTO (SYLVATAL[®] 25/30 S); and CTO obtained from Stora Enso pulping facilities in Finland were used as feeds for hydrotreating experiments. Detailed chemical and elemen-

tal composition and total acid number of the employed feeds are represented in Tables 1 and 2. A commercial alumina (Al₂O₃) supported NiMo catalyst in sulfided form was employed for hydrotreating studies. The pre-sulfidation was carried out by using a H₂S/H₂ mixture for 5 h at 400°C (H₂S/H₂ = 5 vol. %). The test runs (6 h) with each tall oil feed were performed in a continuous down flow fixed bed reactor (stainless steel tube, length: 450 mm long, internal diameter: 15 mm) at different process conditions; temperature = 325–450°C, H₂ partial pressure = 5 MPa, weight hourly space velocity (whsv) = 1–3 h⁻¹ and H₂/feedstock molar ratio = 17.4. Duplicate experiments were carried out for certain test runs so as to check the reproducibility of yield. In a typical experiment, a known amount of the catalyst (6, 3, and 2 g corresponds to WHSV 1 h⁻¹, WHSV 2 h⁻¹, and WHSV 3 h⁻¹) was loaded in the reactor which was then placed in an oven (Oy Meyer Vastus, Monninkylä, Finland). The catalyst bed temperature was monitored by a temperature controller (TTM-339 series). A set amount of feedstock was fed to the reactor along with hydrogen (62 mol/kg of CTO). TOFA and DTO were used as received for hydrotreating experiments, whereas CTO was preheated in order to reduce the viscosity, and thus to enhance the feeding of the material to the reactor. Gas chromatographic tools such as such as GC-MS (HP-5 MS column), GC×GC-MS (ZB-5 HT inferno and ZB-35 HT inferno columns)and GC×GC-FID/(TOF-MS) (Rtx-1 PONA and BPX-50 columns) were used for quantitatively (using external calibration method) and qualitatively analyzing the organic phase samples obtained from hydrotreating of tall oils [22, 23]. GC-FID (DB-23 and Zebron ZB-1 columns) analyses were carried out to calculate the residual amounts of fatty acids, resin acids, and sterols from organic phase samples. The amount (wt%) of water in aqueous phase samples was determined by Karl Fischer (KF) titration (method: ASTM E 203). Analysis of gas phase components was carried out by FT-IR and micro-GC instruments. The residual oxygen composition of organic phase samples from hydrotreated tall oils was determined by elemental analysis using CHN equipment based on ASTM D 5291 method. Sulfur content was determined by means of ASTM D 4239 method.

Terminology and calculations

For the sake of clarity, the term paraffins in this study correspond to *n*-alkanes and *i*-alkanes. Nonaromatics denote cycloalkanes or naphthenes (-mono, -di, or -tri) and other cyclic oxygenates as well as fatty alcohols and unsaturated hydrocarbons. The reactions which mention in this study under hydrotreating conditions are hydrogenation of

Table 1. Feedstock composition.

Composition (wt.%)	TOFA	DTO	CTO	
Free and bonded Fatty Acids	92.6	71.3	48.1	
			Free	Bonded
(16:0) Palmitic acid	0.40	0.20	2.1	0.04
(17:0) Margaric acid	0.80	0.30	0.4	0.01
(18:0) Stearic acid	0.90	0.70	0.8	0.01
(18:1) Oleic acid	27.4	15.3	8.6	0.16
(18:1) 11-octadecenoic acid	0.70	0.50	0.3	0.01
(18:2) 5,9-octadecadienoic acid	0.50	0.30	0.2	0.02
(18:2) conj. octadecadienoic acid	6.00	8.30	5.5	0.36
(18:2) Linoleic acid	23.1	24.3	19.1	2.4
(18:3) Pinolenic acid	8.00	4.4	1.6	0.5
(18:3) Linolenic acid	4.30	0.60	0.6	0.02
(18:3) conj. octadecatrienoic acid	0.20	1.80	0.4	0
(20:0) Arachidic acid	0.80	0.40	0.7	0.01
(20:3) 5,11,14-eicosatrienoic acid	7.90	7.60	1.4	0.08
(20:3) 7,11,14-eicosatrienoic acid	1.30	0.60	0.2	0.2
Other fatty acids	10.3	6.00	1.8	0.28
Free and bonded Resin Acids	1.3	23	28.5	
			Free	Bonded
8,15-isopimaradien-18-oic acid	0.1	0.5		
Pimaric acid	0.7	4.8	2.6	0.03
Sandaracopimaric acid	–	0.3	0.8	0.03
Diabietic acid	–	0.5	–	–
Palustric acid	–	2.2	3.9	0.01
Isopimaric acid	–	1.1	1.3	0.01
7, 9 (11)-abietic acid	–	0.4	0.1	0
13-B-7,9(11)-abietic acid	–	0.3	0.2	0.02
Abietic acid	0.1	7.7	9.1	0.1
Dehydroabietic acid	–	3.6	2.4	0.04
Neoabietic acid	–	0.4	3.3	0.02
Other resin acids	0.4	1.3	2.8	0.7
Neutrals			23	
Campesterol	–	–	0.02	–
Campestanol	–	–	0.17	–
β-Sitosterol	–	–	2.5	–
β-Sitostanol	–	–	0.5	–
Lupeol	–	–	0.5	–
Cycloartenol	–	–	0.2	–
24-methylenecycloartenol	–	–	2.5	–
Prenol-7	–	–	0.07	–
α-Sitosterol	–	–	1.1	–
Methyl betulinate	–	–	0.02	–
Betulin	–	–	0.3	–
Betulinic acid	–	–	0.5	–
Prenol-8	–	–	0.9	–
Other	–	–	12.6	–

Table 2. Elemental composition total acid number (TAN).

Composition	TOFA	DTO	CTO
Elemental composition			
C (wt%)	76.8	77.4	78.6
H (wt%)	11.6	11.1	11.2
O (wt%)	11.6	11.4	9.9
N (ppm)	12	30	100
S (ppm)	53	161	1800
P (ppm)	–	–	36
Alkali metals and alkaline earth metals (ppm)	–	–	56
Total acid number (TAN) mg/kg	326	300	129.5

double bonds, decarboxylation, decarbonylation, HDO, isomerization, hydrocracking of alkane and cyclic structures, and thermal cracking reactions. HDO is represented as a reaction resulted from complete hydrogenation with saturation of double bonds as the first step. Selective deoxygenation denotes the catalytic deoxygenation reactions at low temperatures (Mainly HDO, removal of oxygen as water). Nonselective deoxygenation represents the deoxygenation reactions which occur at high temperatures (thermal or catalytic cracking, removal of oxygen as CO₂).

The mass based yield (%) of various product streams in this study is calculated as a relative yield based on the amount (g/h) of feedstock entering to the reactor. Conversion of fatty acids and resin acids was calculated by assuming that residual acid fractions are mostly present in the organic phase. The equation used for calculating the conversion is

$$\text{Conversion (\%)} = \frac{n_{A, \text{Feed}} - n_{A, \text{O.P.}}}{n_{A, \text{Feed}}} \times 100,$$

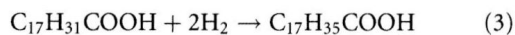
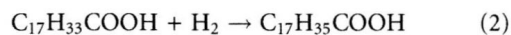
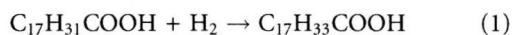
$n_{A, \text{Feed}}$, is the total mol of acids (fatty acid/resin acid) present in the feed, $n_{A, \text{O.P.}}$, is the total mol of acids (fatty acid/resin acid) present in the organic phase.

Product yield of paraffins (n -alkanes + i -alkanes) was calculated by assuming that paraffins are solely formed from fatty acid fraction in tall oils. Product yield was calculated by using the following equation.

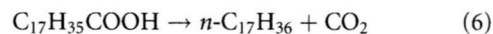
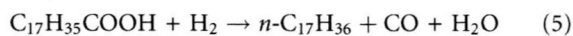
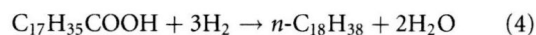
$$\text{Product yield (\%)} = \left[\frac{\text{Total mol of paraffins in O.P.}}{\text{Total mol of fatty acids in Feed}} \right] \times 100$$

The reaction steps discussed in this study in association with the hydrogenation and deoxygenation of fatty acids (linoleic acid and oleic acid) in tall oils over a sulfided NiMo catalyst are shown below by Equations (1), (2), (3), (4), (5), and (6)

Hydrogenation:



Deoxygenation:



Experimental Results

Hydrotreating of TOFA

Hydrotreating experiments with TOFA on a NiMo catalyst resulted in liquid product streams which differ in color and yield depending on the conditions in the reactor. Importantly, the samples from TOFA hydrotreating at low temperatures (<350°C) appeared as oily samples with the tendency of solidification at room temperature. It was also observed that the temperature, 300°C, tested with TOFA resulted the excessive deposition of wax; thus, reactor plugging. In line with earlier studies [22, 23], mass balance error ($\pm 5\%$) was higher in experiments at elevated temperatures (>400°C) in comparison with low-temperature experiments. Liquid products obtained from TOFA hydrotreating were separated into organic and aqueous phases. Table 3 shows the detailed product distribution in organic phases obtained from TOFA hydrotreating at various process conditions. As hydrotreating of TOFA produces more paraffins than other tall oil feeds, the product distribution of major paraffinic hydrocarbons such as n -octadecane and n -heptadecane obtained in TOFA hydrotreating at different process conditions is presented in this study as a separate section.

Product distribution of C₁₇ and C₁₈ hydrocarbons in TOFA hydrotreating

The amount of n -octadecane and n -heptadecane obtained in TOFA hydrotreating on a sulfided NiMo catalyst is shown in Table 3. It is clear from Table 3 that a significant drop in the production n -octadecane occurred with TOFA from 325 to 450°C especially at the longest space time tested (WHSV = 1 h⁻¹), whereas n -heptadecane production steadily increased until 400°C and then sharply decreased at 450°C. As already noted from earlier studies [22, 23], low temperatures (<400°C) are more favorable for the formation of n -octadecane through a HDO route. As the temperature increases, routes consuming less hydrogen such as decarboxylation and decarbonylation are

Table 3. Product distribution of the organic phase obtained from the hydrotreating of TOFA at different process conditions.

Temp (°C)	325	350	400	450	325	350	400	450	325	350	400	450
WHSV (h ⁻¹)	1	1	1	1	2	2	2	2	3	3	3	3
Composition (wt%)												
Paraffins												
<i>n</i> C ₇ -C ₉	0.4	1.2	6.8	10.1	0.9	1.8	4.4	8.3	0.2	0.8	3.1	9.2
<i>n</i> C ₁₀ -C ₁₆	1.4	2.2	4.3	8.6	4.2	2.9	3	14.1	2.8	1.9	4.4	8.3
<i>n</i> C ₁₇	27.7	36	36	27	24	31	31	20	21.5	29	30	23
<i>n</i> C ₁₈	53	44	32	22	49.8	49	35	29	43	41	33	33
<i>n</i> C ₁₉	1.2	1	1.3	2.1	3.8	2.4	0.9	1.1	0.8	0.7	0.6	0.4
<i>n</i> C ₂₀	2	0.8	1.4	1.5	2.4	2.1	0.2	0.9	2.9	1.5	1.4	0.2
<i>i</i> alkanes	2.1	2.5	4.1	6	1.4	1.7	3.4	3	1.4	2.1	2.7	2.9
Total	87.6	87.7	86	78.1	86.5	90.9	77.9	76.4	72.6	77	75.2	77
Nonaromatics												
Cycloalkanes	0.08	0.2	1.4	3	0.9	0.4	0.4	2.5	0	0.03	0.9	0.3
Olefins	0.07	0.4	0	0	0.08	0.03	0.01	0.6	0.1	0.2	0.5	0.6
Alcohols	2.3	3.5	2.7	0.3	0.4	0.4	1.8	1	0.3	1	1	0.9
Other	9.5	7.9	4.9	15.8	5.1	7	9	9.1	13.9	5.9	6.8	6
Total	11.9	12	13	19.1	6.4	7.83	11.2	13.2	14.3	7.13	9.2	7.8
Aromatics												
Monoaromatics	0	0	1.7	4.1	0.07	0.04	0.9	1.4	0	0.04	0.8	1.2
Overall wt%	99.5	99.7	96.7	91.3	93	98.7	90	90	86.9	84	85.2	86
Residual oxygen	0.8	0.8	0.46	0.4	1.3	0.9	0.7	0.9	1.6	1.9	1.1	1

prominent, producing a significant amount of *n*-heptadecane at these temperatures. Higher concentration of *n*-heptadecane over *n*-octadecane was observed beyond 350°C at the longest space time tested (WHSV = 1 h⁻¹). This observation is in agreement with the earlier report on the promotion of decarboxylation route over HDO as a function of increasing temperature on a sulfided NiMo catalyst [28]. It may also imply that decarboxylation + decarbonylation reactions predominate over HDO reaction solely at longer space times, that is, WHSV = 1 h⁻¹ with TOFA. Importantly, in comparison with hydroprocessing of vegetable oils such as rapeseed oil and sunflower oil over a NiMo catalyst [29], a similar yield of *n*-alkanes from TOFA hydrotreating at lower temperature (350°C) was achieved, especially for the *n*-C₁₇ + *n*-C₁₈ fraction. It is noteworthy that the amount of oleic acid (C_{18:1}) and linoleic acid (C_{18:2}) is considerably lower in TOFA compared to the aforementioned vegetable oils. Interestingly, in TOFA hydrotreating, irrespective of space time a similar product distribution of *n*-heptadecane and *n*-octadecane was observed at 400°C.

Comparison of TOFA, DTO, and CTO hydrotreating

Overall product distribution

Figure 1 shows the yield of various product streams obtained as a function of temperature at WHSV = 1 h⁻¹ in hydrotreating of tall oils. As noted from Figure 1,

among the three tall oil feeds tested, TOFA was found to give the highest yield of liquid products and organic products at different temperatures. It was also observed with the employed tall oil feedstocks that the lowest temperature tested (*T* = 325°C) resulted to a maximum yield of liquid products. As expected, maximum gas product yield was obtained at 450°C with each tall oil feeds. At this temperature, the highest yield of gas products was obtained from CTO in comparison with DTO and TOFA. The FT-IR detected gas phase components were CO₂, CO, methane, ethane, ethylene, propane, propylene, and butane. Importantly, lighter alkanes and alkenes were obtained solely at high temperatures especially from CTO and DTO. As can be seen from Figure 1, among three tall oil feedstocks the highest yield of water was obtained from TOFA. The trend with the production of water from tall oils followed the decreasing order as TOFA–DTO–CTO. Water is obtained as a by-product of HDO (hydrogenation/dehydration) reaction during hydrotreating.

Composition of organic phase

Figure 2 shows a comparison of the product composition of organic phase samples as a function of temperature obtained in TOFA, DTO, and CTO hydrotreating at WHSV 1 h⁻¹. As can be seen from Figure 2, maximum amount (wt%) of paraffins was obtained from TOFA among three tall oil feeds. This observation appear as an

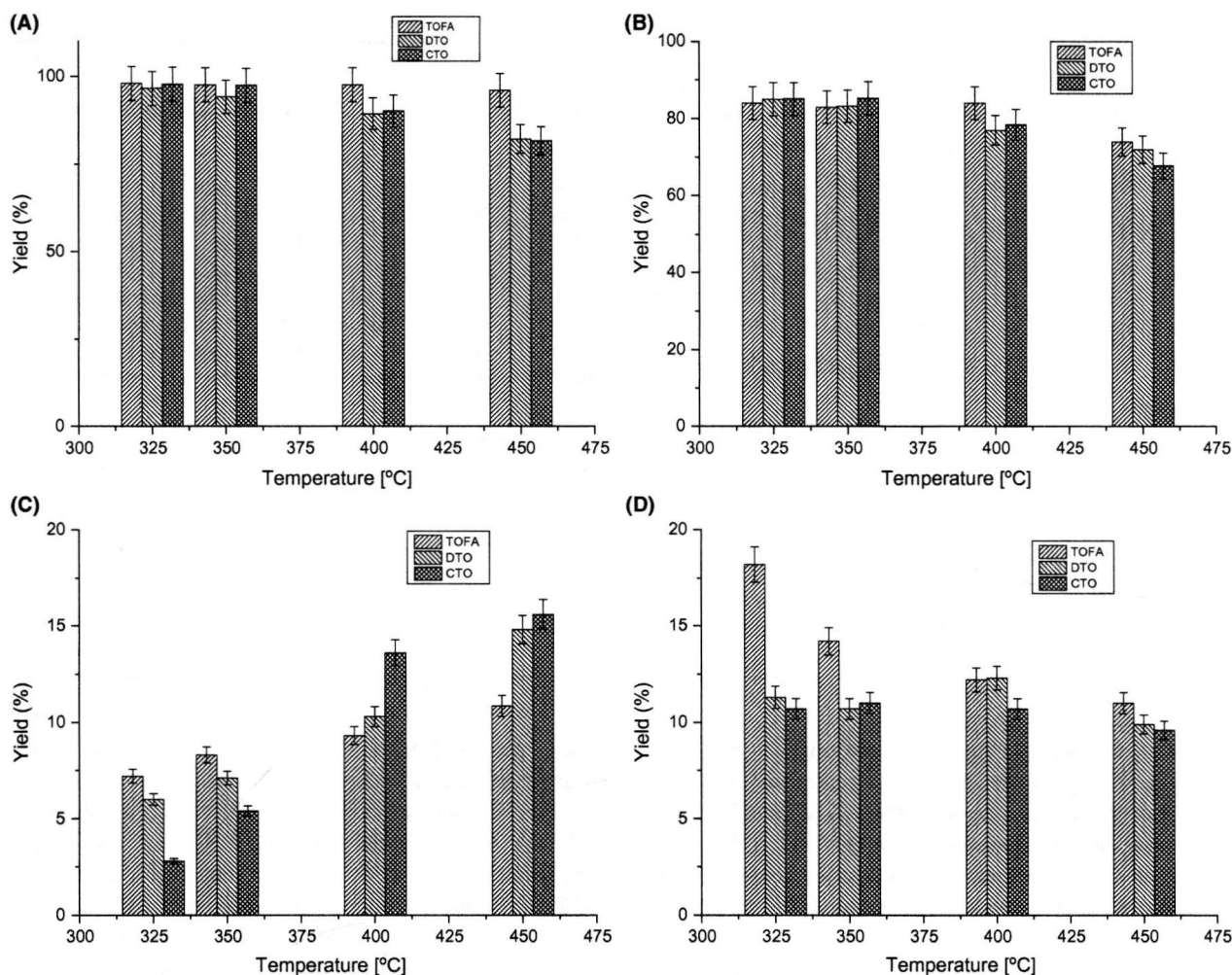


Figure 1. Yield (%) of various product streams obtained in hydrotreating of tall oils over a NiMo catalyst, WHSV = 1 h⁻¹, T = 325–450°C (A) liquid product yield, (B) organic phase product yield, (C) gas product yield, and (D) water yield.

obvious result in relation to the higher amount (wt%) of fatty acids in TOFA.

Product distribution of aromatic and nonaromatic hydrocarbons

As can be seen from Figure 2, nonaromatics such as cyclic structures (monocyclic and polycyclic hydrocarbons), alcohols, unsaturated hydrocarbons, and sterol derivatives were obtained in higher amount with CTO in comparison with other tall oil feeds. Among the three tall oil feeds, maximum production of aromatics was obtained from DTO. It has been reported previously that the aromatics from DTO hydrotreating comprised primarily of monoaromatics such as substituted benzenes in addition to polyaromatics [22]. Organic phases obtained from three feedstocks especially from

CTO also comprised some sulfur (100–500 ppm) and nitrogen (10–20 ppm) [23].

Fatty acid and resin acid conversion

Fatty and resin acid conversions were evaluated based on GC-FID analysis. Figure 3 shows the fatty and resin acid conversions obtained with different tall oil feedstocks at the most favorable space time (WHSV = 1 h⁻¹) as a function of temperatures. Figure 3A shows that fatty acid conversion achieved in a high extent with TOFA and DTO. A similar conversion level achieved with fatty acids in TOFA and DTO in low-temperature hydrotreating experiments (325–400°C). In comparison with TOFA and DTO, a drop in conversion of fatty acids was obtained in CTO hydrotreating under the tested conditions. Figure 3B shows that elevated conversion level was reached for resin