Harnessing ketones as hydrogen acceptors for atom-efficient upgrading of oxygenates to fuels over H/ZSM-5

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Keywords

Synthetic aviation fuel, hydrogen transfer, zeolites, ketones, methanol

Highlights

- Aviation fuel precursor yield is maximized at partial conversion
- Unreacted ketones can be recycled without hindering catalytic performance
- Ketone C=O bonds consume evolved hydrogen and prevent light paraffin formation
- Light olefins are oligomerized to branched aviation range hydrocarbons
- An overall carbon yield from ketones to aviation fuel of 80% is achieved

Abstract

Heterogeneous mixtures of bio-derived oxygenates are promising feedstocks for synthetic aviation fuel (SAF), but conversion strategies for one common component—short-chain (C5-7) internal ketones—are lacking. Previous work has shown that cyclization of ketones over H/ZSM-5 is limited by its high productivity of light paraffins. We study 4-heptanone upgrading over H/ZSM-5 and show that aromatics and olefins can be formed at high carbon yield when operating at up to 90% conversion. The yield of desirable products is not impacted by the introduction of a recycle stream of the unconverted 4-heptanone and other products with similar boiling points. We hypothesize, based on first-principles calculations, that the higher olefin yield is driven by the ease of hydrogen transfer to unreacted ketones as opposed to hydrogenating olefin products. We demonstrate how this ease of hydrogen transfer to ketones can be leveraged to enhance olefin selectivity in the conversion of methanol to olefins as well by co-feeding ketones. Olefinic products of the cyclization reaction are then oligomerized to a SAF blendstock to demonstrate an end-to-end ketone-to-SAF process facilitated by upgrading ketones over H/ZSM-5 at partial conversion with a recycle stream. The results of this work demonstrate a strategy to improve the carbon yield from bio-derived acids to SAF to over 75 %, representing a relative improvement of more than 50% compared to previously reported data.

Introduction

Production of transportation fuels from wet wastes has been identified as an economically attractive strategy to utilize low value materials like food waste, manure, and sewage sludge.[1] Several strategies have been developed to convert low-cost feedstocks into short-chain ($C_{2\text{-}8}$) carboxylic acids as intermediates for fuels production, including fermentation of biomass hydrolysate-derived sugars to butyric acid[2–4] and arrested anaerobic digestion of wet wastes to mixed carboxylic acids.[1,5,6] Carboxylic acids can be subsequently upgraded to ketones via ketonization over solid acid catalysts such as ZrO_2 and TiO_2.[7–13] Ketones in the aviation fuel range (C_{8-16}), can be readily hydrotreated to an n-paraffin SAF blendstock.[14,15] Shorter ketones (C_{3-7}) produced from ketonization of acetic, propanoic, and butyric acids need alternative processing steps to form aviation-range molecules. Several investigations have explored aldol condensation of these ketones over oxide catalysts.[16–20] However, these studies have largely been limited to methyl ketones, with Sun et al.[21] specifically noting that 3-pentanone, an internal (non-methyl) ketone, did not couple with itself over $MgZrO_x$. Other studies have suggested that steric hinderance limits the rate of condensation of internal ketones.[22]

An alternative pathway to aldol condensation is thus needed for upgrading streams rich in internal ketones with fewer than seven carbons. Fufachev et al.,[8] Cao et al.,[23] and Wang et al.[24] all recently explored an alternative pathway, reacting C_{5-7} ketones over H/ZSM-5 in an inert atmosphere to achieve up to 50 % carbon yields to aromatics. Alkyl aromatic molecules are valuable aviation fuel components that are necessary for achieving the elastomer seal swelling needed for engine operation.[25] This approach is also attractive because it produces a hydrocarbon product without the necessity of added H_2. Our group[26] recently observed a similar result during upgrading of a waste-derived mixture of carboxylic acids (primarily acetic and butyric) via ketonization and subsequent reaction over H/ZSM-5. We obtained a 49 % carbon yield to valuable products (SAF-range aromatics; aromatic platform chemicals benzene, toluene, ethylbenzene, and xylenes (BTEX); and naphtha-range alkanes). Technoeconomic analysis indicated that the low carbon selectivity to SAF or BTEX was an economic barrier. In particular, the carbon yield of low value light ($<C_6$) alkanes exceeded 15 % when the ketone feed was completely converted. High selectivity to alkanes is also known to be a challenge for the conversion of methanol to hydrocarbons over HZSM-5,[27,28] and is ascribed to hydrogen transfer from dehydrogenated species to olefins.[29]

In this work, we aim to understand what factors influence the formation of light alkane molecules and propose an improved process for converting C_{3-7} ketones into SAF. We report a strategy to obtain aromatic and branched hydrocarbon SAF blendstocks at high (>80%) yields from butyric acid, with the key step being reaction of 4-heptanone over H/ZSM-5 at incomplete conversion. We first analyzed the reaction network for 4-heptanone upgrading to show that at ketone conversions up to 90%, olefins are only sparingly hydrogenated to paraffins. We then confirmed that unreacted 4-heptanone can be recycled to the reactor influent along with C_{6-8} hydrocarbons of similar boiling point to form the same set of products as neat 4-heptanone feed. We next explored the low rate of light olefin hydrogenation to paraffins at incomplete reactant conversion, despite such hydrogenation occurring during methanol conversion over H/ZSM-5 at equivalent conditions.[30,31] To do this, we co-fed 4-heptanone and methanol over H/ZSM-5 and observed enhanced olefin selectivity compared to methanol alone. This confirmed that ketones can preserve olefins derived from other reactants, enhancing applicability of this SAF production pathway to non-carbonyl-containing reactants. We performed first-principles calculations of hydrogen affinity for relevant olefins and oxygenates to show that ketones are preferentially hydrogenated over olefins in zeolites. Finally, we demonstrated how recovered mixed olefins from the 4-heptanone cyclization can be oligomerized and hydrogenated into SAF range molecules.

Methods

Experimental

The H/ZSM-5 catalyst used in this work for both ketone upgrading and oligomerization was obtained from Zeolyst (CBV8014, Si/Al=40) in NH_4 form and pretreated in stagnant air for 8 hours at 550°C to convert to proton form. An X-ray diffractogram and N_2 physisorption isotherm of the catalyst are shown in Figure S1. The Ni/SiO_2-Al_2O_3 oligomerization catalyst was prepared by incipient wet impregnation of $Ni(NO_3)_2$ on commercial SiO_2-Al_2O_3 (Davicat 3113 obtained from WR Grace). Ni content was 2 wt% as determined by inductive coupled plasma (ICP) analysis. Zeolites and Ni/SiO_2-Al_2O_3 were pelletized and sieved to particle sizes between 117-400 µm before use. Pt/C (10 wt%) powder was obtained from Sigma-Aldrich and used for olefin hydrogenation. Reactant 4-heptanone was obtained from Sigma-Aldrich (98%) and filtered through a 0.45µm PTFE filter disc before use. Reactant methanol was obtained from J.T. Baker (≥99.9%). Helium (Matheson Gas, 99.999%) was used as a sweep gas during vapor-phase reactions. Olefin reactants for oligomerization were obtained from Sigma-Aldrich (1-butene, 2-pentene, 1-pentene, 2-methyl-2-butene, and 1-hexene), Fisher Scientific (1-methylcyclopentene), and Oxarc (ethylene).

Vapor- and three-phase reactions were performed in a Dursan-coated (SilcoTek Coating Co.) stainless steel packed-bed reactor heated by a clamshell furnace and described in our previous work.[7,26] Gases were fed with Brooks Instruments mass flow controllers and combined with liquids fed using a Chrom Tech high-pressure liquid chromatography (HPLC) pump in a 200°C preheating zone upstream of the catalyst bed. Reaction mixtures were flowed downward through a catalyst bed containing 0.1-1 g catalyst supported by a glass wool plug. Temperature was monitored using a concentric thermocouple (Omega) placed inside the catalyst bed. A liquid-cooled heat exchanger operating at 2°C condensed liquid products for collection in a knockout pot, which was emptied periodically (every 2-16 hours). Uncondensed gaseous products were monitored online using an Agilent 6890 gas chromatograph (GC) equipped with an HP-PLOT Q column and a thermal conductivity detector. Reactant consumption was monitored by placing liquid feed reservoirs on Mettler Toledo mass balances and tracking mass changes over time, and liquid product mass was measured similarly. Liquid product samples contained both an organic and aqueous phase, which were separated and independently analyzed. Organic liquid products were diluted in acetone (usually 1:250 v:v), mixed with a nonane internal standard, and analyzed using an Agilent 7890A GC equipped with an Agilent HP-5 MS column, a 5975C mass spectrometer, and a Polyarc quantitative carbon detector (Activated Research Company/Shimadzu). Aqueous liquid products contained only water, except for in experiments with methanol feed-in those cases, methanol content was determined via manual injection into the online Agilent 6890 GC. Catalyst coke was quantified using a Setaram Setsys Evolution thermogravimetric analysis (TGA) system. In these measurements, catalysts were heated to 110 °C at 5 °C/min and held for 30 minutes in an Al_2O_3 pan in flowing N_2 to remove adsorbed water. The gas composition was then changed to dry air (ZeroAir, Matheson) and the sample was heated to 800 °C at 10 °C/min while tracking changes in mass. The reactor system was equipped with a robust process monitoring system that tracks system pressure, temperature, and possible leakages, and shuts down if deviations from expected conditions occur, ensuring operator safety.

Mixed olefin oligomerization experiments were conducted using a fixed bed continuous flow reactor with a total of 2 g catalyst (dual bed catalyst containing 1 g of Ni/SiO_2-Al_2O_3 and H/ZSM-5). The feedstock consisted of an equimolar concentration of ethylene (C_2), propylene (C_3) and a premixed olefin blend of pentene and hexene (C_5/C_6). The detailed composition of C_5/C_6 olefin blend is shown in Table 1.

Table 1. Molar composition of mixed olefin liquid fed along with propylene and ethylene during the mixed olefin oligomerization.

Olefin composition	Mole fraction
2-Pentene	0.326
2-methyl-2-butene	0.239
Methylcyclopentene	0.157
1-Pentene	0.109
1-Hexene	0.169

Carbon balances (CB) were measured using Equation 1 and were always closed within 80% and usually closed within 90%:

$$CB = \frac{\sum_{i = products,\ reactants} C_{n,i}\dot{n}_i}{\sum_{i = reactants} C_{n,i}\dot{n}_{i,0}} \quad (1)$$

Here, $C_{n,i}$ is the carbon number of species i, $n_{i,0}$ is the influent molar flowrate of species i over a time interval, and n_i is the effluent molar flowrate of species i over the same time interval. Carbon yields of each product j (Y_j) were calculated using Equation 2:

$$Y_j = \frac{C_{n,j}\dot{n}_j}{\sum_{i = reactants} C_{n,i}\dot{n}_{i,0}} \quad (2)$$

Conversion of reactant i (X_i) when it was observed in the effluent during single-reactant experiments and overall carbon conversion in cofeed experiments was calculated using Equation 3:

$$X_i = \frac{\sum_{j = products} C_{n,j}\dot{n}_j}{\sum_{i = reactants} C_{n,i}\dot{n}_{i,0}} \quad (3)$$

Conversion was reported as full (100%) when no reactant was left in the effluent. Methanol is assumed to be in equilibrium with dimethyl ether (DME), its bimolecular dehydration product, during reactions of methanol, so DME was not counted as a product in conversion calculations. Conversion was defined for individual reactants in co-feed experiments using Equation 4:

$$X_i = \frac{\dot{n}_i}{\dot{n}_{i,0}} \quad (4)$$

Carbon selectivity of each product j (S_j) was calculated using Equation 5:

$$S_j = \frac{C_{n,j}\dot{n}_j}{\sum_{j = products} C_{n,j}\dot{n}_j} \quad (5)$$

We have shown previously via rigorous heat- and mass-transfer calculations that no significant mass or thermal gradients exist between the bulk gas phase and H/ZSM-5 catalyst particle surfaces (satisfying Mears' criteria).[32] Intraparticle mass transfer gradients do exist, but intraparticle thermal gradients do not.[26]

Computational methods

All gas-phase calculations were performed at the high-level G4MP2 level of theory[33,34] using the Gaussian 16 package.[35] The Gibbs free energies of protonation (ΔG_{prot}) were calculated using Equation 6:

$$\Delta G_{prot} = G_{carbocation} - G_{neutral} - G_{H^+} \tag{6}$$

where $G_{carbocation}$ and, $G_{neutral}$ are the computed Gibbs free energy of the optimized carbocation and the neutral olefin/oxygenate molecule, respectively. A value of -26.34 kJ/mol was used for the Gibbs free energy of the proton (G_{H^+}).[36]

Results

Understanding the correlation between 4-heptanone conversion and paraffin selectivity

Previous work has suggested that the production of $C_{2\text{-}6}$ paraffins is dependent on the level of 4-heptanone conversion.[26] To confirm this observation, the product slate of 4-heptanone reaction over H/ZSM-5 was measured at conversions between 20 % and 100 %. Figure 1a shows the gradual deactivation of H/ZSM-5 with 4-heptanone exposure over three independent reactions performed in a packed-bed reactor. We showed in our recent publication that (i) the H/ZSM-5 catalyst can be regenerated after deactivation by exposure to air at 550°C and (ii) catalyst deactivation is non-selective, meaning that selectivity of all products at a given 4-heptanone conversion will always be the same, regardless of catalyst deactivation.[26] Thus, a reaction network of 4-heptanone upgrading can be postulated by examining trends in product selectivity as a function of $X_{4\text{-heptanone}}$ over single experiments as the catalyst deactivates with time on stream.

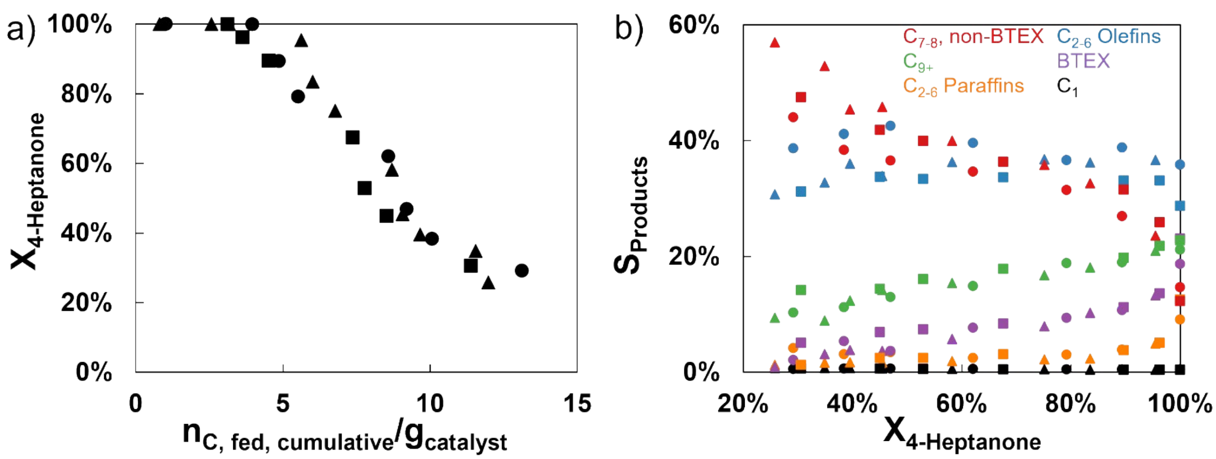


Figure 1. Reaction results for 4-heptanone conversion over H/ZSM-5 during three independent flow reactions represented by circles, triangles, and squares. (a) Conversion of 4-heptanone ($X_{4\text{-Heptanone}}$) as a function of cumulative carbon moles fed per H/ZSM-5 mass; (b) Carbon selectivity of product categories as a function of $X_{4\text{-Heptanone}}$. T: 350°C, P_{Total}=200 kPa, $P_{4\text{-Heptanone}}$=19 kPa, balance He (60-90 sccm), WHSV= 2.5-3 hr^{-1}, $m_{H/ZSM\text{-}5}$=1 g.

Trends in selectivity of major product groups as a function of 4-heptanone conversion are shown to be consistent over multiple independent experiments in Figure 1b. Catalyst coke selectivity was analyzed using thermogravimetric analysis and was determined to be below 1 %. The postulated reaction network for upgrading of 4-heptanone to hydrocarbons has been described previously.[26] Briefly, 4-heptanone initially reacts via two pathways, either (i) dehydration to heptadienes or C_7 cyclic alkenes or (ii) C-C scission to light olefins. Figure 1b shows that these two product groups (with heptadienes or C_7 cyclic alkenes accounting for most of the $C_{7\text{-}8}$, non-BTEX group) account for ~80% carbon selectivity at low $X_{4\text{-Heptanone}}$ (25%, Figure 1). Selectivity to both product groups declines with increasing conversion, showing that these products are subsequently converted into other molecules. The decrease in $C_{7\text{-}8}$, non BTEX selectivity is matched by a concomitant increase in selectivities for BTEX and C_{9+} aromatics, showing that the initially-formed C_7 products are aromatized and (in some cases) alkylated. Decreases in $C_{2\text{-}6}$ olefin selectivity are matched by increases in $C_{2\text{-}6}$ paraffin selectivity, showing that the primary consumption pathway for olefins is hydrogenation to paraffins.

Although $C_{7\text{-}8}$ non-BTEX products and $C_{2\text{-}6}$ olefins are both primary, unstable products, Figure 1b shows that their selectivity trends with conversion are not equivalent. The selectivity of $C_{7\text{-}8}$ non-aromatics decreases continuously with conversion, as would be expected for an unstable product consumed in a successive reaction. The selectivity of $C_{2\text{-}6}$ olefins, meanwhile, stays relatively constant up to ~90% 4-heptanone conversion. This trend is illustrated clearly in Figure 2 (black triangles, squares, and circles), which shows that the yield of $C_{2\text{-}6}$ olefins as a share of all $C_{1\text{-}6}$ products excluding benzene remains above 90% up to 90% 4-heptanone conversion (2a), while the hydrogen transfer index (HTI), a measure of the fraction of $C_{2\text{-}6}$ molecules that are saturated, remains below 10% up to the same conversion (2b). Table S1 collects the mole fractions of all products with boiling points below 80 °C at 83 % 4-heptanone conversion and shows that ethylene and propylene make up nearly 40 mol. % of the light gases, followed by larger olefins. However, the fraction of $C_{2\text{-}6}$ olefins in all $C_{1\text{-}6}$ products decreased sharply above 90 % 4-heptanone conversion, causing the HTI to increase to over 60 %. This change indicates that conversions of 4-heptanone above 90 % favor the rapid consumption of light olefins.

The difference in selectivity trends between $C_{7\text{-}8}$, non-BTEX molecules and $C_{2\text{-}6}$ olefins is counterintuitive, as the former group's selectivity decreases steadily with increasing $X_{4\text{-heptanone}}$, while the latter group maintains relatively constant selectivity up to $X_{4\text{-heptanone}}$~85% and steeply declines at higher conversions (Figure 2b). This contrast is particularly surprising because aromatization, the primary consumption mechanism of $C_{7\text{-}8}$, non-BTEX molecules, releases hydrogen. The transformation of $C_{2\text{-}6}$ olefins into paraffins correspondingly requires hydrogen, but this transformation does not take place. Thus, an alternative hydrogen receptor must prevent light olefin hydrogenation until 4-heptanone conversion is close to complete.

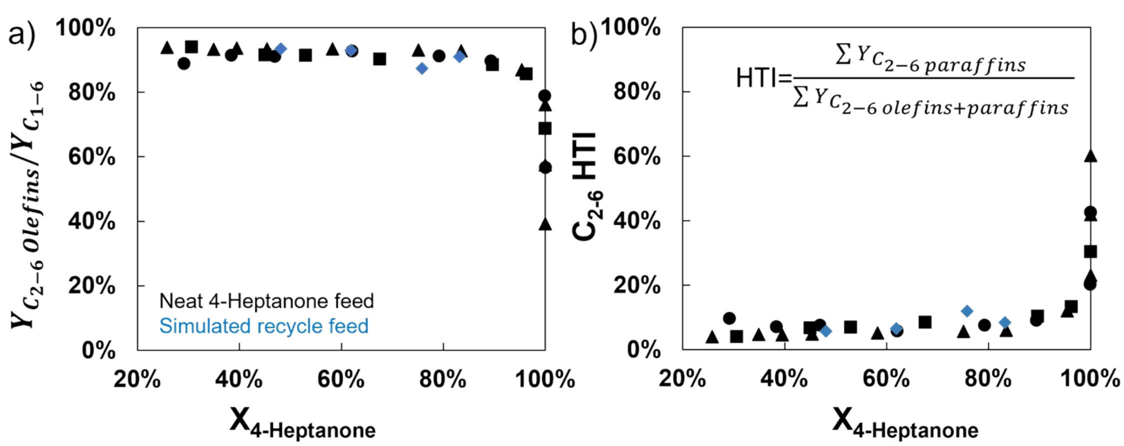


Figure 2. Reaction results for 4-heptanone conversion over H/ZSM-5 during three independent flow reactions compared to a simulated recycle reaction. (a) Carbon ratio of olefins to all hydrocarbon products in the <80°C boiling fraction; (b) $C_{2\text{-}6}$ hydrogen transfer index (HTI). The three black shapes (triangles, squares, and circles) correspond to three independent reactions of 4-heptanone. T: 350°C, P_{Total}=200 kPa, $P_{4\text{-Heptanone}}$=19 kPa, balance He (60-90 sccm), WHSV= 2.5-3 hr^{-1}, $m_{H/ZSM\text{-}5}$=1 g. Blue diamonds correspond to simulated recycle reaction. T: 350°C, P_{total}=160 kPa, He sweep gas (30 sccm), WHSV=2-7 hr^{-1}, $m_{H/ZSM\text{-}5}$=0.3 g. $Y_{C1\text{-}6}$ includes all carbon-containing molecules with carbon numbers between 1-6 besides benzene.

Hydrogen affinity of ketones enhances olefin yields during zeolite upgrading

The "out of sync" trends in cycloalkane aromatization and olefin hydrogenation observed during 4-heptanone upgrading herein are not seen in all oxygenate upgrading reactions over H/ZSM-5. Methanol upgrading to hydrocarbons (MTH) over H/ZSM-5 is an extremely well-characterized reaction system, and many researchers including Bleken et al.[30] and Bjørgen et al.[31] have shown that olefin hydrogenation occurs quite readily during MTH. We directly demonstrate that olefins are readily converted to paraffins during MTH in Figure 3, which shows that, at sub-complete methanol conversions, the yield of olefins among C_{1-6} products is consistently 20% lower (Figure 3a) and HTI of C_{2-6} products is more than three times higher (Figure 3b) compared to the same conversions for 4-heptanone upgrading. However, olefin selectivity and HTI values converge for the two feedstocks near complete conversion. This indicates that olefins are more likely to be hydrogenated in the MTH reaction, while olefin hydrogenation is suppressed during 4-heptanone conversion. This finding remains true when a 50/50 (C:C) mixture of methanol and 4-heptanone is reacted over H/ZSM-5 as the olefin selectivity and HTI are nearly identical to that of a pure 4-heptanone reactant up to a carbon conversion of 80%, indicating that the presence of 4-heptanone suppresses olefin hydrogenation regardless of olefin source. Khare et al.[37] observed a similar drop in olefin hydrogenation when co-feeding acetaldehyde during MTH over H/ZSM-5. Carbon yields of all observed product categories are collected in Figures S2-S4 while the overall carbon conversions for the three feedstocks as a function of time on stream are compared in Figure S5. These results demonstrate that neat 4-heptanone and the 50/50 mixture of 4-heptanone and methanol deactivated at a similar rate and had similar aromatic productivities. The neat methanol feed on the other hand took longer to begin deactivation but deactivated at a faster rate once it started. Furthermore, the methanol alone feed lost nearly all single ring aromatic selectivity once it began to deactivate while 4-heptanone containing feeds maintained higher yields of aromatic products, suggesting that 4-heptanone encouraged the formation of aromatic products.

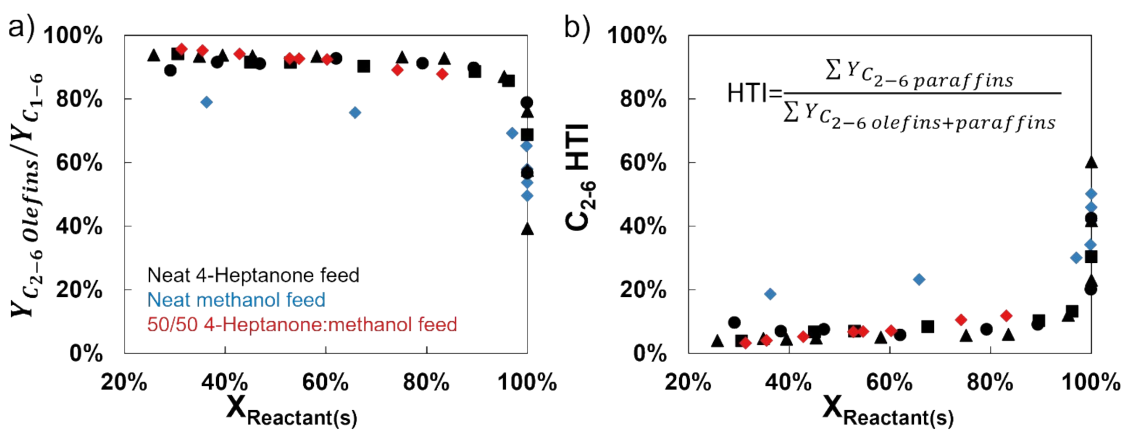


Figure 3. Reaction results for 4-heptanone, methanol, and a blend of 4-heptanone and methanol conversion over H/ZSM-5 during five independent flow reactions. (a) Carbon ratio of olefins to all hydrocarbon products <80°C boiling fraction; (b) C_{2-6} hydrogen transfer index (HTI). Three shapes (triangles, squares, and circles) correspond to three independent reactions of 4-heptanone, blue diamonds correspond to a reaction of methanol, and red diamonds correspond to a reaction of 50/50 (C:C) 4-heptanone:methanol. T: 350°C, P_{Total}=170-200 kPa, He sweep gas flowrate=60-90 sccm; WHSV= 2.5-3 hr^{-1} (pure 4-heptanone), 30-31 hr^{-1} (pure methanol), and 9-10 hr^{-1} (4-heptanone/methanol mixture); $m_{H/ZSM-5}$=1 g (4-heptanone), 0.1 g (methanol), 0.2 g (4-heptanone/methanol mixture). Both methanol and dimethyl ether are counted as unconverted for the purposes of calculating conversion.

We hypothesize that the rerouting of hydrogen transfer pathways causes carbonyl-containing compounds to promote olefin selectivity at the expense of paraffin formation during reactions over H/ZSM-

5. It is well established that reactions of (i) cyclic hydrocarbons to aromatics and (ii) alcohols to aldehydes or ketones (*e.g.*, methanol to formaldehyde) are the two pathways responsible for dihydrogen production during hydrocarbon and oxygenate reactions over H/ZSM-5 and other acid catalysts.[17,38–41] We do not observe H_2 in our reactor effluent, however, and it is not usually observed during reactions over acidic catalysts with no metal functionality under the reactor conditions studied here. Thus, hydrogenation and dehydrogenation reactions must be coupled (hydrogen transfer); every dehydrogenation reactant must transfer two H-atoms to a hydrogen acceptor.

Molecules with non-aromatic double bonds make ideal hydrogen acceptors; thus, relevant acceptors involved in 4-heptanone upgrading are ketones (4-heptanone itself) and olefins. DeLuca et al.[42] recently showed in a computational study that barriers for hydrogenation reactions over zeolites are correlated with stability of carbocations formed via protonation of the hydrogen acceptors double bond. Specifically, a lower Gibbs free energy of protonation (ΔG_{prot}) indicates a more stable carbocation or higher hydrogen affinity. We employed this logic to gauge the ease of hydrogenation among olefins and oxygenates: using accurate G4MP2 method to evaluate ΔG_{prot} of 4-heptanone, methanol, and C_{2-5} alkenes observed during 4-heptanone upgrading and MTH (Figure 4a). The ΔG_{prot} of 4-heptanone is 10 kJ/mol less than that of any alkene considered (-835 kJ mol^{-1} versus -825 kJ mol^{-1} or higher) and significantly less than the ΔG_{prot} of propylene (-757 kJ mol^{-1}) and ethylene (-674 kJ mol^{-1}), the two olefins with the highest selectivity (Table S1). This is in stark contrast with methanol, which has a much higher value of ΔG_{prot} (-747 kJ/mol). These results indicate that hydrogenation of 4-heptanone is more favorable compared to other olefins and oxygenates. Indeed, Ji et al.[43] and Khare et al.[37] both also concluded that aldehydes and ketones are preferentially hydrogenated during oxygenate upgrading over zeolites. Figure 4b illustrates the implications of this finding: When 4-heptanone is present in significant quantities, it will be hydrogenated instead of olefins. This reaction forms 4-heptanol, which rapidly dehydrates to 3-heptene. This molecule will either aromatize or crack to light olefins and paraffins, as shown in Figure 4c. C_7 alcohol or olefin products of hydrogen transfer to 4-heptanone are difficult to observe directly because they are highly reactive and diffusionally constrained and thus unlikely to egress from the zeolite intact. We do not observe any 4-heptanol, likely due to its rapid dehydration. Figure S6 compares the yields of other C_7 products during reactions of 4-heptanone, methanol, and the 50/50 (C:C) mixed feed shown in Figure 3. C_7 yields are 3-4 times higher during reactions of 4-heptanone than the other reactants (Figure S6a), primarily from formation of C_7H_{12} species (Figure S6b), which can come from either dehydration of 4-heptanol or dehydrogenation of 4-heptanol-derived heptene, providing no way to distinguish between the two reaction pathways. Toluene (Figure S6c) is also formed at higher yields when pure 4-heptanone is fed compared to methanol or mixtures. Yields of C_7H_{14} species, our hypothesized primary product of 4-heptanol dehydration, are low (<1%, Figure S6d) during every reaction, although maximum yields (observed between 50-80% reactant conversion) increase slightly from 0.64 C % without 4-heptanone to 0.93 C % with 4-heptanone as the feed. These species could, however, be formed via alternative pathways such as C-C bond formation between olefins. The low-to-nonexistent yields of obvious 4-heptanone hydrogenation products (4-heptanol and C_7H_{14} species) indicates their high reactivity in the zeolite.

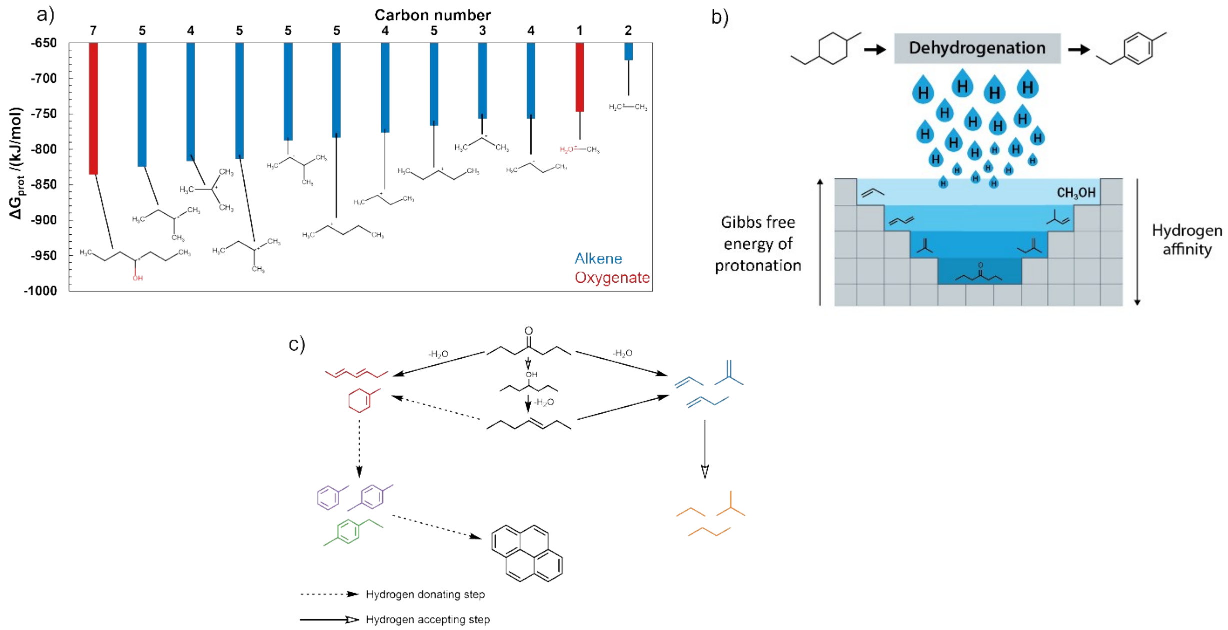


Figure 4. (a) Comparison of calculated Gibbs free energy of protonation (ΔG_{prot}) of olefins and oxygenates observed during 4-heptanone upgrading and MTH. (b) Schematic of hydrogen transfer from aromatizing cycloalkanes to oxygenates and alkenes, where molecules capable of forming stable carbenium ions (low ΔG_{prot}) are advantaged hydrogen acceptors. (c) Simplified reaction network for 4-heptanone upgrading, highlighting steps involving hydrogen donation and acceptance. Molecule colors correspond to product lump colors in Figure 1b.

Figure 4c also shows that cracking of C_7H_{14} species can form olefins. We show in Figure S7 the yields of all $C_{2\text{-}6}$ products (Figure S7a), olefins (Figure S7b), and paraffins (Figure S7c) as a function of reactant conversion. Feeds of methanol result in higher yields of all these products compared to mixed 4-heptanone/methanol feeds or solely 4-heptanone, making assignment of olefins as products of cracking of a specific C_7 species difficult. Olefins can be formed from 4-heptanone cracking as well as C_7H_{14} cracking, although the former reaction necessitates production of equimolar amounts of dienes and olefins, as shown in Equations 7a and 7b:

$$C_7H_{14}O \rightarrow H_2O + C_nH_{2n-2} + C_mH_{2m} \; (n+m=7) \quad (7a)$$

$$C_7H_{14} \rightarrow C_nH_{2n} + C_mH_{2m} \; (n+m=7) \quad (7b)$$

We do not observe significant production of any dienes with carbon numbers below C_7 during 4-heptanone reactions, showing that either (i) the major production route for olefins is through cracking of heptenes derived from 4-heptanone hydrogenation or (ii) dienes of chain lengths below C_7 are rapidly consumed via hydrogenation or aromatization. Since it is unlikely that C_7 dienes, which are observed, are uniquely resilient compared to dienes of lower carbon number, we posit that (i) is true and that observed olefin production results from cracking of 4-heptanone hydrogenation-derived heptenes via the following sequence of reactions:

$$C_7H_{14}O + RH_2 \rightarrow C_7H_{15}OH + R \quad (8a)$$

$$C_7H_{15}OH \rightarrow C_7H_{14} + H_2O \quad (8b)$$

$$C_7H_{14} \rightarrow C_nH_{2n} + C_mH_{2m} \; (n+m=7) \quad (8c)$$

In Equations 8a-b, RH_2 is a hydrogen donor and R is its dehydrogenated analogue. Figure S7b shows more evidence for the hypothesis of hydrogen transfer to 4-heptanone enhancing olefin selectivity, as olefin yields at low (<60%, and especially <30%) reactant conversion are higher when 4-heptanone and methanol are co-fed than when either is individually fed. This is likely because 4-heptanone is accepting hydrogen from methanol dehydration to formaldehyde at these conditions,[40,41] increasing flux of carbon through the pathway in Equation 8.

If no 4-heptanone is present (as in the case of a neat methanol feed), olefins will be hydrogenated to paraffins. This results in higher paraffin yields at equivalent conversions using pure methanol feeds than feeds containing 4-heptanone as shown in Figure S7c and as a higher HTI in Figure 3b. Olefins that form the lowest-energy carbocations upon protonation are preferentially hydrogenated. Figure 4c illustrates the role of 4-heptanone in the reaction network as a H-acceptor and highlights steps which release hydrogen (C_7H_{12} aromatization, aromatic growth to deactivation-causing polyaromatics, and heptane dehydrogenation) and accept hydrogen (4-heptanone and olefin hydrogenation).

The trend in H-acceptor energy explains the data in Figs 1-3. While 4-heptanone is abundant in the zeolite ($X_{4\text{-heptanone}}$<90%), selectivity to olefins is high (30-40%) while selectivity to paraffins (<5%) and HTI (<10%) are both low. This trend is not seen for methanol, a molecule with a much higher ΔG_{prot}. However, as 4-heptanone becomes scarce ($X_{4\text{-heptanone}}$>90%), paraffin selectivity and HTI both rapidly increase, such that the HTIs of both methanol and 4-heptanone upgrading converge at between 30 and 60% at full reactant conversion (Figure 3b).

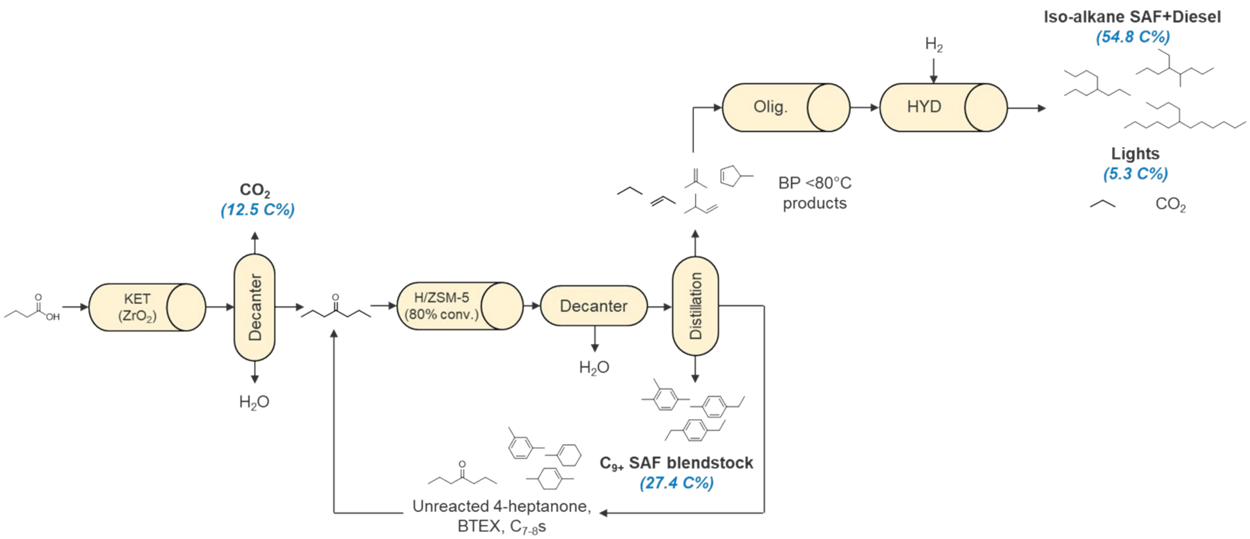
The hydrogen uptake of 4-heptanone can also be empirically observed by examining products of 4-heptanone aromatization via reactions such as Equation 9:

$$C_7H_{14}O \rightarrow C_7H_8 + H_2O + 2[H_2] \tag{9}$$

In Equation (9), $[H_2]$ is placed in brackets because no H_2 is observed; hydrogen transfer to other molecules is facile. Following the analysis of Khare et al.,[37] if olefins were the only hydrogen acceptors available, we should expect to see two paraffins formed by olefin hydrogenation for every aromatic. However, the ratio of paraffins to aromatics is much lower than this, below 0.5 up to 99% $X_{4\text{-heptanone}}$, showing hydrogenation of a different molecule must be occurring. Our analysis herein shows that this hydrogen acceptor is 4-heptanone and that the presence of this ketone during oxygenate upgrading over H/ZSM-5 results in uniquely high $C_{2\text{-}6}$ olefin selectivities, enabling upgrading of butyric acid and other similar molecules to aromatic SAF and olefins.

Oligomerization of simulated olefin stream offers increased aviation fuel yields

The above findings demonstrate that operation of the 4-heptanone conversion reactor at partial (below 80%) conversion leads to improved light olefin selectivity. However, these light olefins require further processing to become liquid transportation fuels. Several ASTM approved SAF concepts, including the alcohol to jet pathway, rely on oligomerization and hydrotreating to convert olefins into SAF-range alkanes.[44–47] Scheme 1 shows how the application of this concept can be incorporated into our previously-developed strategy to upgrade VFAs with fewer than four carbon atoms, such as butyric acid, into a SAF blendstock containing both aromatic and iso-alkane components. Briefly, butyric acid is ketonized over ZrO_2 to 4-heptanone in a packed-bed reactor, as has been demonstrated in previous work from our group and others.[7–9,15,26] The product 4-heptanone is, after separation from co-products CO_2 and water, fed to a reactor containing H/ZSM-5 operated at 80% conversion. Since H/ZSM-5 deactivates with time on stream under these conditions (Figure 1a),[24,26,48] this reactor would need to allow for regular catalyst regeneration (validated in our previous work)[26] and could take forms such as a swing bed or moving bed. The partially converted effluent of the ketone upgrading reactor would be separable into four streams: water, light and naphthenic hydrocarbons (primarily olefins) with boiling points <80°C, C_{9+} aromatics and polyaromatics with boiling points >144°C, and a middle hydrocarbon stream consisting of unreacted 4-heptanone with BTEX and $C_{7\text{-}8}$ non-aromatic molecules. The aqueous phase can be decanted, and the remaining three hydrocarbon streams could be separated via distillation.



Scheme 1. Conceptual design of a process to upgrade butyric acid to SAF and diesel fuel based on experimental results. Bolded molecule categories show final products of the process; carbon selectivities to these are displayed in blue parentheses below each product. KET=Ketonization, Olig.=oligomerization, and HYD=hydrogenation.

The heavy C_{9+} aromatic stream can be used directly as a SAF blendstock, as shown in our previous work.[26] Figure 2a shows that the light stream (boiling points <80°C) consists of ~90% alkenes, which can be oligomerized and hydrotreated to a mixture of jet- and diesel-range iso-alkanes (see below). This stream will also contain a small percentage of light alkanes, which can either be burned for process heat or, if desired, alkylated with the oligomer stream before hydrotreating to further increase carbon yield to fuels.[49,50] The unreacted 4-heptanone, BTEX, and $C_{7\text{-}8}$ non-aromatic molecules can be recycled into the H/ZSM-5 reactor influent. BTEX molecules could also be separated from this stream using an additional extraction method, as suggested by Yadav et al,[26,51] but we exclude this step from our proposed strategy. Scheme 1 shows the carbon selectivity to each effluent stream, assuming ideal separations and using H/ZSM-5 reactor effluents at 80% conversion described in Figure 1. Under this scheme, 82.2% of influent carbon exits the system as SAF and diesel fuel, a marked improvement from the 49% carbon yield from $C_{2\text{-}4}$ carboxylic acids to SAF, BTEX, and naphtha that we previously demonstrated using H/ZSM-5 at full conversion.[26]

The efficacy of the strategy shown in Scheme 1 hinges on the performance of two steps: (i) upgrading a recycled feed of 4-heptanone, BTEX, and $C_{7\text{-}8}$ hydrocarbons over H/ZSM-5 with the same performance as neat 4-heptanone and (ii) complete oligomerization of the primarily olefinic stream of products with boiling point <80°C from the H/ZSM-5 ketone upgrading reactor. We tested upgrading of a recycled feed by collecting and combining liquid partial conversion products of the three pure 4-heptanone reactions shown in Figures 1 and 2 into the mixture shown in Table S2. The mixture contained mostly 4-heptanone (74.4 C%), with a balance of $C_{7\text{-}8}$ non-BTEX hydrocarbons (18.3 C%) and <3 C% each of BTEX, C_{9+} aromatics, $C_{2\text{-}6}$ olefins, and $C_{2\text{-}6}$ paraffins. The 4-heptanone content of this mixture is equivalent to running the H/ZSM-5 reactor at 80% 4-heptanone conversion and a recycle ratio (mass flow of recycle stream/mass flow of reactor inlet stream) of 0.84. Catalytic performance of this mixture (blue diamonds) is compared to that of neat 4-heptanone (black triangles, squares, and circles) in Figure 2, where the trends in yield of C_{2-6} olefins as a share of C_{1-6} products (2a) and C_{2-6} HTI (2b) are shown to be identical between the simulated recycle and neat 4-heptanone reactor feeds. Production of C_{9+} aromatics also remains unchanged at these simulated recycle conditions. Thus, H/ZSM-5 is effective at upgrading a mixed feed of 4-heptanone and hydrocarbon products with boiling points between 80 and 144°C to the same products as neat 4-heptanone.

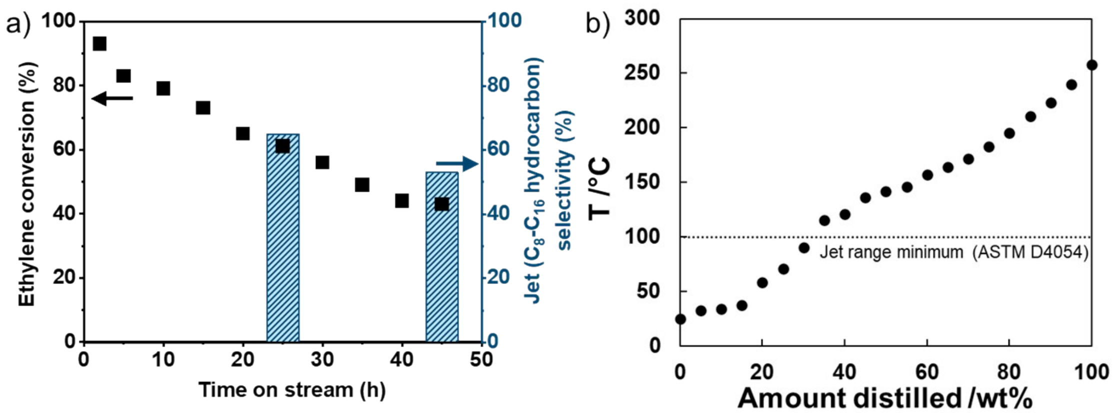


Figure 5. (a) Ethylene conversion (black square) and jet (C_8-C_{16} olefins) selectivity (blue bar) obtained during mixed olefin oligomerization (T = 250 °C; P = 21 bar; WHSV = 0.7 h^{-1}) and (b) simulated distillation (ASTM D2887) of isoparaffin products of olefin oligomerization and hydrotreating (samples corresponding to 25 h demonstrated in Figure 3a was used herein for analysis).

The second critical step for the process is oligomerization of the olefin effluent of the H/ZSM-5 reactor. The content of the boiling point <80°C stream at $X_{4\text{-heptanone}}$=83%, the proposed inlet to an oligomerization process, is shown in Table S1 and shows that <C_6 olefins make up over 84 mol. % of the stream. We next oligomerized a representative mixture of olefins using a stacked bed reactor composed of (i) Ni/SiO_2-Al_2O_3 and (ii) H/ZSM-5. This proof-of-concept experiment was carried out using a feedstock of ethylene, 1-butene, 1-pentene, 2-pentene, 2-methyl-2-butene, methylcyclopentene and 1-hexene. Ethylene oligomerization proceeded via a Cosse-Arlman pathway over the Ni catalyst, while the C_{4+} alkenes from both the original feed and ethylene oligomerization were oligomerized over the downstream zeolite via acid-catalyzed pathways.[52,53] Performance and catalyst stability during oligomerization was monitored by the change in ethylene conversion over time as it can be measured unambiguously. Figure 5a shows ~95% of ethylene conversion was obtained at the beginning of the reaction; however, conversion decreased continuously over time. Detailed analysis of the liquid product showed that selectivity to jet range compounds i.e., C_8-C_{16} hydrocarbons was 65% and 53% after 25 and 45 h respectively (blue bars in Figure 5a). Next, the oligomerized olefins (samples collected after 25 h) were hydrotreated in a lab-scale trickle-bed reactor over 10 wt% Pt/C (T=250°C, P_{H2}=3500 kPa, WHSV=0.9 hr^{-1}). Roughly half of the fed oligomers were transformed into SAF-range isoparaffins, as 67% of the mass fed to the reactor was recovered, while Figure 5b shows that 65% of collected products were in the jet range (100-330°C as defined for Simulated Distillation by ASTM D4054[54]). All non-SAF products were light paraffins derived from non- or under-oligomerized olefins. The results herein highlight the feasibility of oligomerization to upgrade the light olefin mixture to SAF. Focused research is currently underway to optimize performance and identify the cause of oligomerization catalyst deactivation.

Conclusions

This work showed that carbonyl-containing organic reactants such as 4-heptanone can be reacted over H/ZSM-5 at incomplete conversion to form aromatic and (via subsequent light olefin oligomerization) isoparaffinic SAF blendstocks at high carbon yield. Our studies of the 4-heptanone upgrading reaction network evinced high olefin and aromatic selectivity up to 90% reactant conversion. Co-feeds of 4-heptanone with upgrading products with similar boiling points showed no difference in product distribution, meaning that these products can be recycled to the H/ZSM-5 reactor influent. First-principles calculations showed that the high hydrogen affinity of ketones attenuates olefin hydrogenation until most ketones are converted while co-feed experiments with 4-heptanone and methanol proved that even olefins derived from non-ketone sources can be preserved from hydrogenation by ketones. Finally, this work also demonstrated the feasibility of oligomerizing light olefins into alkane SAF range molecules using a single mixed catalyst bed. Overall, these experiments outline a potential strategy to convert over 80 % of the carbon in $<C_7$ ketones into liquid fuels. This result enhances the overall fuel yields in the carboxylic acids upgrading pathway by converting internal ketones into fuels.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence this work.

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