

METHOD OF PROVIDING A BIO-OIL TO A HYDRODEOXYGENATION REACTOR

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of and priority to U.S. Provisional Appl. No. 62/984,260, filed March 2, 2020, the contents of which are incorporated by reference in their entirety for any and all purposes.

FIELD

The present technology relates to conversion of biorenewable feedstocks to hydrocarbons.

BACKGROUND

Renewable diesel (RD) is an isoparaffinic compression ignition fuel produced by hydroprocessing of fats and oils. The process comprises hydrodeoxygenation (HDO) of fatty acids/glycerides to hydrocarbons rich in n-paraffins. The HDO step may be followed by hydroisomerization (HI) of the n-paraffins to isoparaffins. Most HDO processes are conducted in adiabatic fixed-bed reactor systems comprising a sulfided base metal catalyst such as NiMo on γ -alumina support.

Since the HDO reaction is exothermic, a diluent is often used to mitigate the adiabatic temperature rise across the reactor and minimize undesirable side reactions. The diluent may be a petroleum-based or a bio-based hydrocarbon liquid. An example of a petroleum-based hydrocarbon diluent suitable for HDO is straight run diesel from crude oil distillation, while an example of a bio-based hydrocarbon is the product of fatty acid/glyceride HDO that is partially recycled to the reactor with fresh fatty acid/glyceride feed.

1 Commercial production of RD began in 2007 and has grown to over 1.5 billion gal/y
2 worldwide today. In order to ensure feedstock availability, producers have been exploring
3 use of lower quality bio-oil feedstock such as used cooking oils, trap greases, and palm
4 sludge oil.

5 The greenhouse gas impact of any given fuel may be quantified by its Carbon
6 Intensity (C.I.). C.I. is a measure of the life-cycle greenhouse gas emissions of a fuel relative
7 to the energy obtained through its combustion. Depending on feedstock, RD has a C.I. value
8 between 30 and 50 g CO₂e/MJ as estimated using the CA-GREET3.0 model provided by
9 California Air Resources Board. The 30-50 g CO₂e/MJ C.I. range compares to 70-80 g
10 CO₂e/MJ for bioethanol and 100+ CO₂e/MJ for petroleum diesel. Generally, the best/lowest
11 C.I. values are provided by the lower quality bio-oil feedstock. For example, RD produced
12 by used cooking oil has a C.I. of 30 g CO₂e/MJ or less.

13 These lower quality bio-oils have a number of contaminants that negatively impact
14 HDO performance. For example, the rate of reactor fouling (including fouling of reactor
15 internals and catalyst) is increased with more contaminated feeds. The prior art discloses that
16 iron contaminants can cause accelerated plugging. Phosphorous and metals other than iron
17 have also been cited in prior art literature as causing reactor fouling issues and catalyst
18 deactivation. Fouling may also be caused by polymerization of the reactive components in
19 bio-oil. Such reactive components include free fatty acids, polyunsaturated fatty acids, and
20 oxidation byproducts of fatty acids.

21 There is thus a need for method to mitigate fouling in bio-oil HDO reactors such that
22 lower quality bio-oil feedstock is efficiently converted into low carbon intensity fuels.

SUMMARY

Water is a byproduct of HDO reactions. Depending on the oxygen content of the bio-oil, the water byproduct is typically between 5% and 20% of the total liquid product mass. Although most water can be removed from the hydrogen and hydrocarbon recycle streams by conventional separation methods such as vapor-liquid and liquid-liquid separation, some water remains in these process streams that are combined with fresh bio-oil feed to the reactor.

These hydrogen and hydrocarbon streams comprising water vapor are characterized by a water dew point. Water dew point, in general, is the temperature at which water droplets form in a vapor stream (or in the vapor fraction of a two-phase stream wherein the liquid fraction is a hydrocarbon). Water dew point is generally a function involving the concentration of water in the vapor phase; the higher the water concentration, the higher the water dew point.

It has surprisingly been observed that when a bio-oil is introduced into a diluent comprising a hydrocarbon liquid and water vapor, the difference between the diluent's water dew point and the bio-oil temperature can impact the rate of reactor fouling. Specifically, when the water dew point is higher than the temperature of the bio-oil feed by more than 50 °F, accelerated reactor fouling is observed.

Without being bound to theory, it is believed by the inventors that fouling is accelerated by formation of water droplets around which foulant particles that are formed at high temperature can coalesce and agglomerate. Due to the mixing dynamics that occur when the diluent and bio-oil are brought together, such water droplets may form and cause fouling of the reactor internals and catalyst bed. The water dew point of the diluent and the temperature of the bio-oil when it comes in contact therewith has thus shown to be a predictor

1 of this phenomenon and one basis for a method of the present technology for mitigating
2 fouling when processing low-value/waste fats and oils.

3 Thus, in an aspect, a method for hydrodeoxygenation of a bio-oil over a catalyst bed
4 in an HDO reactor is provided where the method includes combining (i) a two-phase diluent
5 having a water dew point and (ii) a bio-oil at a bio-oil temperature that is from about 50 °F
6 less than to about 100 °F more than the water dew point. In the method, the two-phase
7 diluent includes a liquid phase and a vapor phase. The liquid phase includes a hydrocarbon
8 and the vapor phase includes hydrogen and water. Therefore, in any embodiment herein of
9 the process, the bio-oil temperature may be about 50 °F less than the water dew point, about
10 45 °F less than the water dew point, about 40 °F less than the water dew point, about 35 °F
11 less than the water dew point, about 30 °F less than the water dew point, about 25 °F less than
12 the water dew point, about 20 °F less than, the water dew point about 15 °F less than the
13 water dew point, about 10 °F less than the water dew point, about 5 °F less than the water
14 dew point, the same as (*i.e.*, 0 °F from) the water dew point, about 5 °F more than the water
15 dew point, about 10 °F more than the water dew point, about 15 °F more than the water dew
16 point, about 20 °F more than the water dew point, about 25 °F more than the water dew point,
17 about 30 °F more than the water dew point, about 35 °F more than the water dew point, about
18 40 °F more than the water dew point, about 45 °F more than the water dew point, about 50 °F
19 more than the water dew point, about 55 °F more than the water dew point, about 60 °F more
20 than the water dew point, about 65 °F more than the water dew point, about 70 °F more than
21 the water dew point, about 75 °F more than the water dew point, about 80 °F more than the
22 water dew point, about 85 °F more than the water dew point, about 90 °F more than the water
23 dew point, about 95 °F more than the water dew point, about 100 °F more than the water dew
24 point, or any range including and/or in between any two of these values. In any embodiment
25 of the method, it may be that the bio-oil temperature is from 20 °F to 0 °F less than the water

1 dew point. In any embodiment of the method, it may be that the bio-oil temperature is from
2 10 °F to 0 °F less than the water dew point. In any embodiment of the method, it may be that
3 the bio-oil temperature from 0 °F to 20 °F more than the water dew point of the two-phase
4 diluent.

5 In any embodiment of the method, it may be that method comprises combining the
6 bio-oil and the two-phase diluent in a mix-tee. In any embodiment of the method, it may be
7 that the method comprises combining the bio-oil and the two-phase diluent through a static-
8 mixer. In any embodiment of the method, it may be that combining the bio-oil and the two-
9 phase diluent comprises directing the bio-oil through a quill within a pipe, wherein the pipe
10 provides the two-phase diluent. In any embodiment of the method, it may be that the bio-oil
11 comprises poultry fats, poultry oil, vegetable fats, rendered fats, rendered oils, restaurant
12 grease, brown grease, yellow grease, used cooking oil, waste industrial frying oils, fish oils,
13 fish fats, algal oils, microbial oils, or a combination of any two or more thereof. In any
14 embodiment of the method, it may be that the method produces a renewable diesel, wherein
15 the renewable diesel has a carbon intensity of 30 gCO₂e/MJ or less according to California
16 Air Resource Board CA-GREET3.0 model. In any embodiment of the method, it may be that
17 fouling of the HDO reactor as evidenced by a pressure drop increase of no more than 10 psi
18 during the service life of the catalyst. In any embodiment of the method, it may be that
19 combining the two-phase diluent and the bio-oil provides a diluted bio-oil, and wherein the
20 process further comprises contacting the diluted bio-oil with the catalyst bed to provide a
21 catalyst bed outlet product. In any embodiment of the method, it may be that prior to
22 combining the two-phase diluent and the bio-oil, the method comprises adjusting the bio-oil
23 temperature to be from 50 °F less than to 50 °F more than the water dew point. In any
24 embodiment of the method, it may be that prior to combining the two-phase diluent and the

1 bio-oil, the process comprises measuring the two-phase diluent to determine the water dew
2 point.

3 BRIEF DESCRIPTION OF THE DRAWINGS

4 FIG. 1 provides a schematic diagram of an operation for producing renewable diesel
5 according to an embodiment of the present technology.

6 FIG. 2 provides a graph of data from studies according to the working examples,
7 involving two pilot plant HDO reactors (R1 and R2) of the same makeup and catalyst
8 composition, and run under the same conditions with the same feed with the exception that
9 the feed of R1 was spiked with 3% water while no water was added to the feed of R2.

10 DETAILED DESCRIPTION

11 Various embodiments are described hereinafter. It should be noted that the specific
12 embodiments are not intended as an exhaustive description or as a limitation to the broader
13 aspects discussed herein. One aspect described in conjunction with a particular embodiment
14 is not necessarily limited to that embodiment and can be practiced with any other
15 embodiment(s).

16 The following terms are used throughout as defined below.

17 As used herein and in the appended claims, singular articles such as “a” and “an” and
18 “the” and similar referents in the context of describing the elements (especially in the context
19 of the following claims) are to be construed to cover both the singular and the plural, unless
20 otherwise indicated herein or clearly contradicted by context. Recitation of ranges of values
21 herein are merely intended to serve as a shorthand method of referring individually to each
22 separate value falling within the range, unless otherwise indicated herein, and each separate
23 value is incorporated into the specification as if it were individually recited herein. All

1 methods described herein can be performed in any suitable order unless otherwise indicated
2 herein or otherwise clearly contradicted by context. The use of any and all examples, or
3 exemplary language (*e.g.*, “such as”) provided herein, is intended merely to better illuminate
4 the embodiments and does not pose a limitation on the scope of the claims unless otherwise
5 stated. No language in the specification should be construed as indicating any non-claimed
6 element as essential.

7 As used herein, “about” will be understood by persons of ordinary skill in the art and
8 will vary to some extent depending upon the context in which it is used. If there are uses of
9 the term which are not clear to persons of ordinary skill in the art, given the context in which
10 it is used, “about” will mean up to plus or minus 10% of the particular term – for example,
11 “about 10 weight %” would be understood to mean “9 weight % to 11 weight %.” It is to be
12 understood that when “about” precedes a term, the term is to be construed as disclosing
13 “about” the term as well as the term without modification by “about” – for example, “about
14 10 wt.%” discloses “9 wt.% to 11 wt.%” as well as disclosing “10 wt.%.”

15 The phrase “and/or” as used in the present disclosure will be understood to mean any
16 one of the recited members individually or a combination of any two or more thereof – for
17 example, “A, B, and/or C” would mean “A, B, C, A and B, A and C, or B and C.”

18 As used herein, “alkyl” groups include straight chain and branched alkyl groups.
19 Examples of straight chain alkyl groups include methyl, ethyl, n-propyl, n-butyl, n-pentyl, n-
20 hexyl, n-heptyl, and n-octyl groups. Examples of branched alkyl groups include, but are not
21 limited to, isopropyl, sec-butyl, t-butyl, neopentyl, and isopentyl groups. It will be
22 understood that the phrase “C_x-C_y alkyl,” such as C₁-C₄ alkyl, means an alkyl group with a
23 carbon number falling in the range from *x* to *y*.

1 “Oxygenates” as used herein means carbon-containing compounds containing at least
2 one covalent bond to oxygen. Examples of functional groups encompassed by the term
3 include, but are not limited to, carboxylic acids, carboxylates, acid anhydrides, aldehydes,
4 esters, ethers, ketones, and alcohols, as well as heteroatom esters and anhydrides such as
5 phosphate esters and phosphate anhydrides. Oxygenates may also be oxygen containing
6 variants of aromatics, cycloparaffins, and paraffins as described herein.

7 The term “paraffins” as used herein means non-cyclic, branched or unbranched
8 alkanes. An unbranched paraffin is an n-paraffin; a branched paraffin is an iso-paraffin.
9 “Cycloparaffins” are cyclic, branched or unbranched alkanes.

10 The term “paraffinic” as used herein means both paraffins and cycloparaffins as
11 defined above as well as predominantly hydrocarbon chains possessing regions that are
12 alkane, either branched or unbranched, with mono- or di-unsaturation (*i.e.*, one or two double
13 bonds).

14 Hydroprocessing as used herein describes the various types of catalytic reactions that
15 occur in the presence of hydrogen without limitation. Examples of the most common
16 hydroprocessing reactions include, but are not limited to, hydrogenation,
17 hydrodesulfurization (HDS), hydrodenitrogenation (HDN), hydrotreating (HT),
18 hydrocracking (HC), aromatic saturation or hydrodearomatization (HDA),
19 hydrodeoxygenation (HDO), decarboxylation (DCO), hydroisomerization (HI),
20 hydrodewaxing (HDW), hydrodemetallization (HDM), decarbonylation, methanation, and
21 reforming. Depending upon the type of catalyst, reactor configuration, reactor conditions,
22 and feedstock composition, multiple reactions can take place that range from purely thermal
23 (*i.e.*, do not require catalyst) to catalytic. In the case of describing the main function of a
24 particular hydroprocessing unit, for example an HDO reaction system, it is understood that

1 the HDO reaction is merely one of the predominant reactions that are taking place and that
2 other reactions may also take place.

3 Decarboxylation (DCO) is understood to mean hydroprocessing of an organic
4 molecule such that a carboxyl group is removed from the organic molecule to produce CO₂,
5 as well as decarbonylation which results in the formation of CO.

6 Pyrolysis is understood to mean thermochemical decomposition of carbonaceous
7 material with little to no diatomic oxygen or diatomic hydrogen present during the
8 thermochemical reaction. The optional use of a catalyst in pyrolysis is typically referred to as
9 catalytic cracking, which is encompassed by the term as pyrolysis, and is not be confused
10 with hydrocracking.

11 Hydrotreating (HT) involves the removal of elements from groups 3, 5, 6, and/or 7 of
12 the Periodic Table from organic compounds. Hydrotreating may also include
13 hydrodemetallization (HDM) reactions. Hydrotreating thus involves removal of heteroatoms
14 such as oxygen, nitrogen, sulfur, and combinations of any two more thereof through
15 hydroprocessing. For example, hydrodeoxygenation (HDO) is understood to mean removal
16 of oxygen by a catalytic hydroprocessing reaction to produce water as a by-product;
17 similarly, hydrodesulfurization (HDS) and hydrodenitrogenation (HDN) describe the
18 respective removal of the indicated elements through hydroprocessing.

19 Hydrogenation involves the addition of hydrogen to an organic molecule without
20 breaking the molecule into subunits. Addition of hydrogen to a carbon-carbon or carbon-
21 oxygen double bond to produce single bonds are two nonlimiting examples of hydrogenation.
22 Partial hydrogenation and selective hydrogenation are terms used to refer to hydrogenation
23 reactions that result in partial saturation of an unsaturated feedstock. For example, vegetable
24 oils with a high percentage of polyunsaturated fatty acids (*e.g.*, linoleic acid) may undergo

1 partial hydrogenation to provide a hydroprocessed product wherein the polyunsaturated fatty
2 acids are converted to mono-unsaturated fatty acids (*e.g.*, oleic acid) without increasing the
3 percentage of undesired saturated fatty acids (*e.g.*, stearic acid). While hydrogenation is
4 distinct from hydrotreatment, hydroisomerization, and hydrocracking, hydrogenation may
5 occur amidst these other reactions.

6 Hydrocracking (HC) is understood to mean the breaking of a molecule's carbon-
7 carbon bond to form at least two molecules in the presence of hydrogen. Such reactions
8 typically undergo subsequent hydrogenation of the resulting double bond.

9 Hydroisomerization (HI) is defined as the skeletal rearrangement of carbon-carbon
10 bonds in the presence of hydrogen to form an isomer. Hydrocracking is a competing reaction
11 for most HI catalytic reactions and it is understood that the HC reaction pathway, as a minor
12 reaction, is included in the use of the term HI. Hydrodewaxing (HDW) is a specific form of
13 hydrocracking and hydroisomerization designed to improve the low temperature
14 characteristics of a hydrocarbon fluid.

15 It will be understood that if a composition is stated to include " C_x - C_y hydrocarbons,"
16 such as C_7 - C_{12} n-paraffins, this means the composition includes one or more paraffins with a
17 carbon number falling in the range from x to y .

18 A "diesel fuel" in general refers to a fuel with boiling point that falls in the range from
19 about 150 °C to about 360 °C (the "diesel boiling range").

20 A "petroleum diesel" as used herein refers to diesel fuel produced from crude oil,
21 such as in a crude oil refining facility and includes hydrotreated straight-run diesel,
22 hydrotreated fluidized catalytic cracker light cycle oil, hydrotreated coker light gasoil,
23 hydrocracked FCC heavy cycle oil, and combinations thereof. A "petroleum-based

1 hydrocarbon liquid” or “petroleum-based hydrocarbon diluent” as used herein refers to
2 hydrocarbons produced from crude oil, such as in a crude oil refining facility and includes
3 hydrotreated straight-run diesel, hydrotreated fluidized catalytic cracker light cycle oil,
4 hydrotreated coker light gasoil, hydrocracked FCC heavy cycle oil, and combinations thereof.

5 It is to be understood that a “volume percent” or “vol.%” of a component in a
6 composition or a volume ratio of different components in a composition is determined at 60
7 °F based on the initial volume of each individual component, not the final volume of
8 combined components.

9 The Present Technology

10 The present technology relates to a method of producing renewable diesel from a bio-
11 oil feedstock comprising low-value and waste fats, oil, and greases (FOG). The method
12 comprises hydrodeoxygenation of the bio-oil in at least one fixed-bed reactor. The bio-oil is
13 combined with a heated diluent characterized by a water dew point. In the present
14 technology, the bio-oil temperature is maintained at a temperature no greater than 50 °F
15 cooler than the water dew point of the diluent. The method of this disclosure reduces the rate
16 of fouling in the fixed-bed reactor.

17 Referring to the non-limiting embodiment depicted in FIG. 1, a bio-oil 101 is
18 transferred to a charge pump surge drum 10. The bio-oil comprises low-value/waste FOG
19 including animal fats and vegetable selected from the group comprising poultry fats, poultry
20 oil, vegetable fats, rendered fats, rendered oils, restaurant grease, brown grease, yellow
21 grease, used cooking oil, waste industrial frying oils, fish oils, fish fats, algal oils, microbial
22 oils, or a combination of any two or more thereof. The bio-oil 101 may or may not comprise
23 (i) oils extracted or pressed from the seeds of energy crops such as carinata, jatropha, and
24 castor seeds, (ii) plant oils recovered as byproducts of edible oil production operations such

1 as palm sludge oil, or (iii) a combination of any one or more embodiment of (i) and/or (ii).
2 The bio-oil 101 may include oils derived from chemical or thermal liquefaction of cellulosic
3 biomass. Fast pyrolysis is an example of a thermal liquefaction process and the bio-oil
4 product thereof is sometimes referred to as pyrolysis oil. Even after pretreatment, bio-oils
5 may contain up to 10 ppm phosphorus and up to 10 ppm total metals (including iron, calcium,
6 magnesium, sodium, and potassium).

7 Regardless of the source and contaminants, the bio-oil 101 typically has an elemental
8 oxygen content from about 5 wt % to about 20 wt %, where the “elemental oxygen content”
9 of a bio-oil is in reference to oxygen atoms in fatty acids and other biological compound, not
10 *e.g.*, water. In any embodiment disclosed herein, the bio-oil 101 may have an elemental
11 oxygen content from about 8 wt % to about 16 wt % of the bio-oil.

12 The bio-oil 101 may include between 5 and 80 wt % free fatty acids (FFA).
13 Additionally, the bio-oil 101 may have a water content of 0.1 to 1.0 wt % as measured by
14 Karl Fisher titration. The water in the bio-oil may be present as dissolved water, free water,
15 and/or emulsified water.

16 The surge drum liquid 102 is pressurized to a reactor inlet pressure via pump 12 to
17 provide a pressurized bio-oil 103. The pressurized bio-oil 103 is split into two streams – bio-
18 oil split stream 104 and bio-oil split stream 105. Bio-oil split stream 104 is combined with a
19 heated diluent 120 in an inline mixing device 16 to provide a first diluted bio-oil 107.

20 The heated diluent 120 may include at least some of the hydrogen required for the
21 HDO reaction. As such, the heated diluent 120 may be a two phase fluid comprising
22 hydrocarbon liquid and a hydrogen-rich gas. In any embodiment herein, it may be heated
23 diluent 120 is a single-phase liquid wherein hydrogen is dissolved in the hydrocarbon liquid.
24 In any embodiment disclosed herein, it may be the heated diluent 120 has a water content

1 between about 0.5 and 4.0 wt %. Regardless of the embodiment, the heated diluent 120 has a
2 water dew point between 210 °F and 350 °F. The process involves maintaining a difference
3 between (a) the water dew point of the heated diluent 120, and (b) the temperature of the bio-
4 oil split stream 104, such that the temperature of the bio-oil split stream is from 50 °F less
5 than the water dew point to 100 °F higher than the water dew point. For example, if the
6 water dew point of the heated diluent 120 is 300 °F, the temperature of the bio-oil split
7 stream 104 is maintained at no cooler than 250 °F. In any embodiment disclosed herein, it
8 may be the bio-oil is no more than 40 °F cooler than the diluent 120 water dew point
9 temperature. In any embodiment disclosed herein, it may be the bio-oil is no more than 30 °F
10 cooler than the diluent 120 water dew point temperature. In any embodiment disclosed
11 herein, it may be the bio-oil is no more than 20 °F cooler than the diluent 120 water dew
12 point. In any embodiment disclosed herein, it may be the bio-oil is between 10 °F and 50 °F
13 cooler than the diluent 120 water dew point. In any embodiment disclosed herein, it may be
14 the bio-oil temperature is the same or higher than the diluent 120 water dew point. As such,
15 the water droplet formation and consequent reactor fouling issues are mitigated.

16 Inline mixing device 16 may be a mix-tee, a static mixer, a pipe with an injection quill
17 (e.g. where split stream 104 enters through a quill into a pipe for mixing with the heated
18 diluent 120), or other similar device known to a person of ordinary skill in the art.

19 The first diluted bio-oil 107 enters HDO reactor 20. The reactor 20 includes at least
20 one bed of catalyst 22. Notably, in the present technology, when the reactor contains only
21 one bed of catalyst, the pressurized bio-oil feed is not split.

22 The bed of catalyst 22 includes a sulfided base metal catalyst supported on γ -alumina.
23 The sulfided base metal catalyst comprises Ni, Mo, Co, W, or a combination of any two or
24 more thereof.

1 The HDO reactor 20 is operated at a Weighted Average Bed Temperature (WABT)
2 between 550 °F and 700 °F. WABT is given by Eq. 1 below where T_{in} and T_{out} respectively
3 refer to temperatures at the inlet and outlet of the catalyst bed.

$$4 \qquad \qquad \qquad WABT = T_{in} + 2/3 (T_{out} - T_{in}) \qquad \qquad (1)$$

5 The HDO reactor 20 may operate under a hydrogen partial pressure between 600 and
6 2,200 psi, preferably between 1,000 and 1,800 psi. The hydrogen may be supplied via the
7 heated diluent 120 and/or directly to the reactor (not shown). An example of the latter is
8 quench hydrogen introduced between the catalyst beds. In any embodiment disclosed herein,
9 the hydrogen may be supplied to the reactor at a gas-to-oil ratio between 5,000 SCFB and
10 20,000 SCFB (wherein the ratio refers to standard cubic feet of H_2 to barrels of bio-oil). The
11 bio-oil 101 is processed through the reactor at a liquid hourly space velocity between 0.2 and
12 10.0 h^{-1} (vol/h of bio-oil per vol of catalyst). At these conditions, the bio-oil split stream 104
13 is at least mostly converted to a catalyst bed outlet product 108.

14 The catalyst bed outlet product 108 comprises hydrogen gas and the liquid product of
15 bio-oil HDO conversion. As such, the catalyst bed outlet product 108 is a two phase fluid
16 comprising hydrocarbon liquid and a hydrogen-rich gas. In any embodiment disclosed
17 herein, it may be the catalyst bed outlet product 108 has a water content between 2.0 and 6.0
18 wt %. Regardless of the embodiment, the heated diluent 120 has a water dew point between
19 240 °F and 350 °F.

20 The bio-oil split stream 105 is heated through a heat exchanger 14 to provide a heated
21 bio-oil 106. The heat exchanger 14 is preferably a shell and tube exchanger with steam
22 condensation on the shell side. In any embodiment herein, the heat exchanger 14 may
23 include a heater with superheated water providing the heat. In any embodiment herein, the
24 heat exchanger 14 may include a heater with a heat transfer fluid providing the heat.

1 The heated bio-oil 106 is combined with the catalyst bed outlet product 108 in a
2 reactor internal mixing device 23 to form a second diluted bio-oil 109. The mixing device 23
3 may be a mixing box, a distributor tray, or any other reactor internal apparatus suitable for
4 mixing two different streams together as understood by a person of ordinary skill in that art.

5 Regardless of the mixing device 23, the temperature of the heated bio-oil 106 is from
6 about 50 °F less than to about 100 °F greater than the water dew point of the catalyst bed
7 outlet product 108. For example, if the water dew point of the catalyst bed outlet product 108
8 is 350 °F, the temperature of the heated bio-oil 106 is maintained at no cooler than 300 °F. In
9 any embodiment disclosed herein, it may be the heated bio-oil 106 is no more than 40 °F
10 cooler than the catalyst bed outlet product 108 water dew point temperature. In any
11 embodiment disclosed herein, it may be the heated bio-oil 106 is no more than 30 °F cooler
12 than the catalyst bed outlet product 108 water dew point. In any embodiment disclosed
13 herein, it may be the heated bio-oil 106 is no more than 20 °F cooler than the catalyst bed
14 outlet product 108 water dew point. In any embodiment disclosed herein, it may be the
15 heated bio-oil 106 is between 10 °F and 50 °F cooler than the catalyst bed outlet product 108
16 water dew point. In any embodiment herein, the heated bio-oil 106 may be heated to a
17 temperature that is the same or higher than the water dew point of the catalyst bed outlet
18 product 108, diluting the heated bio-oil 106. As such, water droplet formation and
19 consequent reactor fouling issues are mitigated (*e.g.*, by reducing the rate of deposit
20 formation and accumulation on bed of catalyst 22). In any embodiment herein, the overall
21 pressure-drop increase due to fouling across the bed of catalyst 22 may be less than 10 psi
22 over the service life of the catalyst.

23 The reactor effluent 110 is cooled through a feed-effluent exchanger 30 to provide a
24 partially cooled effluent 111 before being cooled in a cooler 32 to provide a cooled effluent
25 112. The cooled effluent 112 is at a temperature between 300 °F and 400 °F such that the

1 water byproduct of HDO is mostly in the vapor phase. The cooled effluent 112 is separated
2 into a HPS liquid stream 110A and a vapor stream 124 in a high pressure separator (HPS) 34.
3 The HPS liquid stream 110A comprises the liquid product of HDO conversion, mainly
4 hydrocarbons in the C10-C24 range. The HPS liquid stream 110A is partially recycled as a
5 recycle stream 113 through recycle pump 36 to provide a pressurized recycle stream 115.
6 The pressurized recycle stream 115 is combined with hydrogen 132 to provide a hydrogen-
7 containing diluent stream 118. The hydrogen-containing diluent stream 118 is heated
8 through the aforementioned feed-effluent exchanger 30 to provide a partially heated
9 hydrogen-containing diluent stream 119. This stream is subsequently heated in a diluent
10 heater 46 to provide the heated diluent 120 described earlier herein. The diluent heater 46 is
11 preferably a shell and tube exchanger with hot oil circulation or a fired heater.

12 Returning to the HPS 34, the HPS separator vapor 124 is contacted with a wash water
13 stream 125 before cooling and condensation in an air cooler 40. The cooled and partially
14 condensed stream 126 exits the air cooler 40 at a temperature between 80 °F and 180 °F. The
15 cooled and partially condensed stream 126 is directed to a separation and gas treatment vessel
16 42 where a liquid effluent 128 comprising water is separated from a hydrogen-rich gas stream
17 129. In order to enhance removal of the gas phase byproducts of HDO such as hydrogen
18 sulfide and carbon dioxide, an absorption liquid 127 may be introduced to the separation and
19 gas treatment vessel 42. The absorption liquid 127 may be water or any aqueous solutions
20 comprising sodium hydroxide or amine compounds. In any embodiment disclosed herein, the
21 hydrocarbon stream 128A may be drawn from a separation and gas treatment vessel 42 and
22 further processed to obtain hydrocarbon products. The gas product from the separation and
23 gas treatment vessel 42 is mostly recycled as a recycle hydrogen-rich gas 130 while
24 maintaining a purge/bleed 129A. The recycle hydrogen-rich gas 130 is combined with a

1 makeup hydrogen 131 and directed to a hydrogen compressor 44 for providing hydrogen to
2 the HDO reactor system described herein.

3 Returning to the HPS 34, a portion of the HPS liquid stream 110A is directed to a
4 stripper 50 as liquid product 114. The flow rate of HPS liquid 110A recycled as bio-oil
5 diluent (Stream 113) relative to liquid product stripped (Stream 114) is between 2:1 and 5:1,
6 preferably between 2.5:1 and 4:1. The stripper 50 utilizes a stripping gas 121 to remove any
7 dissolved byproducts of the HDO reaction—*e.g.*, hydrogen sulfide, ammonia, and water—
8 from the paraffinic diesel product 122. The stripped components plus the stripping gas 121
9 are shown leaving the stripper 50 as stream 123. The paraffinic diesel product 122 is a C₁₀-
10 C₂₄ hydrocarbon product with 0.5 to 3.0 wt % C₂₄+ hydrocarbons and a cloud point in the 18-
11 22 °C range. In embodiments, the paraffinic diesel product 122 is subjected to
12 hydrocracking/isomerization as taught in the prior art to reduce the cloud point of the diesel
13 to a value below 0 °C, preferably in the range of -30 °C to -8 °C.

14 The renewable diesel product produced according to the present technology may have
15 a carbon intensity less than 50 gCO₂e/MJ, preferably less than 40 gCO₂e/MJ, and most
16 preferably less than 30 gCO₂e/MJ. The renewable diesel process thus disclosed achieves
17 production of such advantageous fuels while maintaining overall pressure-drop increase due
18 to fouling across catalyst beds at less than 10 psi over the service life of the catalyst.

19 The present technology, thus generally described, will be understood more readily by
20 reference to the following examples, which are provided by way of illustration and are not
21 intended to be limiting of the present technology.

EXAMPLES

Example 1.

Two commercial scale HDO reactors with same catalyst loading and operating under the same conditions with the same bio-oil feedstock were found to foul at different rates as evidenced by rate of pressure drop increase. The water dew point of the diluent to the first reactor (diluted bio-oil) was estimated via Hysys process simulation software using Peng Robinson VLE thermodynamic model and found to be 215 °F. Using the same methodology, the feed to the second reactor was found to have a water dew point of 348 °F. The diluent to each reactor was combined with the same temperature bio-oil (~ 165 °F) directly upstream of the respective reactor. The first reactor with a smaller difference between bio-oil temperature and diluent water dew point temperature did not show any signs of pressure-drop increase during service life. The second reactor with a larger difference between bio-oil temperature and diluent water dew point exhibited pressure-drop increase during the same period and had to be shut down.

Example 2.

Two identical pilot plant HDO reactors were loaded with the same catalyst. No pressure drop was observed across either reactor after a few weeks of operation with a refined, bleached, and deodorized soybean oil feedstock containing 11% technical grade oleic acid (as free fatty acid), diluted with an isoparaffinic hydrocarbon in the diesel boiling range. Both reactors were then switched to run on the same blend of low-value fats, oils, and grease comprising used cooking oil and palm sludge oil, diluted in the same isoparaffinic hydrocarbon diluent. Reactor 1 (R1) was spiked with 3% water whereas Reactor 2 (R2) was used as control (no added water). As shown in FIG. 2, after about 7.5 days, rapid pressure-drop increase was observed in R1 while R2 pressure-drop remained essentially unchanged.

1 The reactors were subsequently opened and inspected. Significantly higher fouling/deposit
2 was observed in R1 than R2.

3 While certain embodiments have been illustrated and described, a person with
4 ordinary skill in the art, after reading the foregoing specification, can effect changes,
5 substitutions of equivalents and other types of alterations to the compounds of the present
6 technology or salts, pharmaceutical compositions, derivatives, prodrugs, metabolites,
7 tautomers or racemic mixtures thereof as set forth herein. Each aspect and embodiment
8 described above can also have included or incorporated therewith such variations or aspects
9 as disclosed in regard to any or all of the other aspects and embodiments.

10 The present technology is also not to be limited in terms of the particular aspects
11 described herein, which are intended as single illustrations of individual aspects of the present
12 technology. Many modifications and variations of this present technology can be made
13 without departing from its spirit and scope, as will be apparent to those skilled in the art.
14 Functionally equivalent methods within the scope of the present technology, in addition to
15 those enumerated herein, will be apparent to those skilled in the art from the foregoing
16 descriptions. Such modifications and variations are intended to fall within the scope of the
17 appended claims. It is to be understood that this present technology is not limited to
18 particular methods, reagents, compounds, compositions, labeled compounds or biological
19 systems, which can, of course, vary. It is also to be understood that the terminology used
20 herein is for the purpose of describing particular aspects only, and is not intended to be
21 limiting. Thus, it is intended that the specification be considered as exemplary only with the
22 breadth, scope and spirit of the present technology indicated only by the appended claims,
23 definitions therein and any equivalents thereof.

24 The embodiments, illustratively described herein may suitably be practiced in the
25 absence of any element or elements, limitation or limitations, not specifically disclosed

1 herein. Thus, for example, the terms “comprising,” “including,” “containing,” etc. shall be
2 read expansively and without limitation. Additionally, the terms and expressions employed
3 herein have been used as terms of description and not of limitation, and there is no intention
4 in the use of such terms and expressions of excluding any equivalents of the features shown
5 and described or portions thereof, but it is recognized that various modifications are possible
6 within the scope of the claimed technology. Additionally, the phrase “consisting essentially
7 of” will be understood to include those elements specifically recited and those additional
8 elements that do not materially affect the basic and novel characteristics of the claimed
9 technology. The phrase “consisting of” excludes any element not specified.

10 In addition, where features or aspects of the disclosure are described in terms of
11 Markush groups, those skilled in the art will recognize that the disclosure is also thereby
12 described in terms of any individual member or subgroup of members of the Markush group.
13 Each of the narrower species and subgeneric groupings falling within the generic disclosure
14 also form part of the invention. This includes the generic description of the invention with a
15 proviso or negative limitation removing any subject matter from the genus, regardless of
16 whether or not the excised material is specifically recited herein.

17 As will be understood by one skilled in the art, for any and all purposes, particularly
18 in terms of providing a written description, all ranges disclosed herein also encompass any
19 and all possible subranges and combinations of subranges thereof. Any listed range can be
20 easily recognized as sufficiently describing and enabling the same range being broken down
21 into at least equal halves, thirds, quarters, fifths, tenths, etc. As a non-limiting example, each
22 range discussed herein can be readily broken down into a lower third, middle third and upper
23 third, etc. As will also be understood by one skilled in the art all language such as “up to,”
24 “at least,” “greater than,” “less than,” and the like, include the number recited and refer to

1 ranges which can be subsequently broken down into subranges as discussed above. Finally,
2 as will be understood by one skilled in the art, a range includes each individual member.

3 All publications, patent applications, issued patents, and other documents (for
4 example, journals, articles, and textbooks) referred to in this specification are herein
5 incorporated by reference as if each individual publication, patent application, issued patent,
6 or other document was specifically and individually indicated to be incorporated by reference
7 in its entirety. Definitions that are contained in text incorporated by reference are excluded to
8 the extent that they contradict definitions in this disclosure.

9 The present technology may include, but is not limited to, the features and
10 combinations of features recited in the following lettered paragraphs, it being understood that
11 the following paragraphs should not be interpreted as limiting the scope of the claims as
12 appended hereto or mandating that all such features must necessarily be included in such
13 claims:

- 14 A. A method for hydrodeoxygenation of a bio-oil over a catalyst bed in a
15 hydrodeoxygenation reactor ("HDO reactor"), the method comprising combining a
16 two-phase diluent having a water dew point and a bio-oil at a bio-oil temperature that
17 is from 50 °F less than to 100 °F more than the water dew point;
18 wherein the two-phase diluent comprises a liquid phase and a vapor phase, the
19 liquid phase comprising a hydrocarbon and the vapor phase comprising
20 hydrogen and water.
- 21 B. The method of Paragraph A, wherein the bio-oil temperature is from 20 °F to 0 °F less
22 than the water dew point.
- 23 C. The method of Paragraph A or Paragraph B, wherein the bio-oil temperature is from 10 °F
24 to 0 °F less than the water dew point.
- 25 D. The method of Paragraph A, wherein the bio-oil temperature from 0 °F to 20 °F more
26 than the water dew point of the two-phase diluent.

- 1 E. The method of any one of Paragraphs A-D, the method comprising combining the bio-oil
2 and the two-phase diluent in a mix-tee.
- 3 F. The method of any one of Paragraphs A-E, the method comprising combining the bio-oil
4 and the two-phase diluent through a static-mixer.
- 5 G. The method of any one of Paragraphs A-F, wherein combining the bio-oil and the two-
6 phase diluent comprises directing the bio-oil through a quill within a pipe, wherein the
7 pipe provides the two-phase diluent.
- 8 H. The method of any one of Paragraphs A-G, wherein the bio-oil comprises poultry fats,
9 poultry oil, vegetable fats, rendered fats, rendered oils, restaurant grease, brown
10 grease, yellow grease, used cooking oil, waste industrial frying oils, fish oils, fish fats,
11 algal oils, microbial oils, or a combination of any two or more thereof.
- 12 I. The method of any one of Paragraphs A-H, wherein the method produces a renewable
13 diesel, wherein the renewable diesel has a carbon intensity of 30 gCO₂e/MJ or less
14 according to California Air Resource Board CA-GREET3.0 model.
- 15 J. The method of any one of Paragraphs A-I, wherein fouling of the HDO reactor as
16 evidenced by a pressure drop increase of no more than 10 psi during the service life of
17 the catalyst.
- 18 K. The method of any one of Paragraphs A-J, wherein combining the two-phase diluent and
19 the bio-oil provides a diluted bio-oil, and wherein the process further comprises
20 contacting the diluted bio-oil with the catalyst bed to provide a catalyst bed outlet
21 product.
- 22 L. The method of any one of Paragraphs A-K, wherein prior to combining the two-phase
23 diluent and the bio-oil, the method comprises adjusting the bio-oil temperature to be
24 from 50 °F less than to 100 °F more than the water dew point.
- 25 M. The method of any one of Paragraphs A-L, wherein prior to combining the two-phase
26 diluent and the bio-oil, the process comprises measuring the two-phase diluent to
27 determine the water dew point.
- 28 N. A method for hydrodeoxygenation of bio-oils over a catalyst bed comprising the steps

- 1 (a) providing a bio-oil;
2 (b) providing a two-phase diluent wherein the two phases include a liquid comprising
3 a hydrocarbon and a vapor phase comprising hydrogen and water; and
4 (c) combining the bio-oil with the two-phase diluent
5 wherein
6 the two-phase diluent is characterized by a water dew point and
7 the bio-oil temperature is at most 50 F below the water dew point of the two-phase
8 diluent.
- 9 O. The method of Paragraph N wherein the bio-oil temperature is at most 20 F below the
10 water dew point of the two-phase diluent.
- 11 P. The method of Paragraph N or Paragraph O wherein the bio-oil temperature is at most 10
12 F below the water dew point of the two-phase diluent.
- 13 Q. The method of Paragraph N wherein the bio-oil temperature is above the water dew point
14 of the two-phase diluent.
- 15 R. The method of any one of Paragraphs N-Q wherein the bio-oil and the two-phase diluent
16 are combined in a mix-tee.
- 17 S. The method of any one of Paragraphs N-R wherein the bio-oil and the two-phase diluent
18 are combined through a static-mixer.
- 19 T. The method of any one of Paragraphs N-S wherein the bio-oil and the two-phase diluent
20 are combined by providing the bio-oil through a quill within a pipe providing the two-
21 phase diluent.
- 22 U. The method of any one of Paragraphs N-T wherein the bio-oil comprises poultry fats,
23 poultry oil, vegetable fats, rendered fats, rendered oils, restaurant grease, brown
24 grease, yellow grease, used cooking oil, waste industrial frying oils, fish oils, fish fats,
25 algal oils, microbial oils and combinations thereof.
- 26 V. The method of any one of Paragraphs N-U wherein the method produces a renewable
27 diesel, wherein the renewable diesel has a carbon intensity of 30 gCO₂e/MJ or less
28 according to California Air Resource Board CA-GREET3.0 model.
- 29 W. The method of any one of Paragraphs N-V wherein hydrodeoxygenation of the bio-oil
30 over the catalyst bed occurs in a hydrodeoxygenation reactor (“HDO reactor”),

1 wherein fouling of the HDO reactor as evidenced by a pressure drop increase of no
2 more than 10 psi during the service life of the catalyst.

3

4 Other embodiments are set forth in the following claims, along with the full scope of
5 equivalents to which such claims are entitled.

WHAT IS CLAIMED IS:

1. A method for hydrodeoxygenation of a bio-oil over a catalyst bed in a hydrodeoxygenation reactor (“HDO reactor”), the method comprising combining a two-phase diluent
5 having a water dew point of 210 °F to 350 °F and the bio-oil at a bio-oil temperature that is from 50 °F less than to 100 °F more than the water dew point;
after combining, contacting the two-phase diluent and the bio-oil with the catalyst bed, the catalyst bed having a weighted average bed temperature of 550°F to 700°F;
wherein the two-phase diluent comprises a liquid phase and a vapor phase, the liquid
10 phase comprising a hydrocarbon and the vapor phase comprising hydrogen and water.
2. The method of Claim 1, wherein the bio-oil temperature is from 20 °F to 0 °F less than the water dew point.
3. The method of Claim 1 or Claim 2, wherein the bio-oil temperature is from 10 °F to 0 °F less than the water dew point.
- 15 4. The method of Claim 1, wherein the bio-oil temperature is from 0 °F to 20 °F more than the water dew point of the two-phase diluent.
5. The method of Claim 1, the method comprising combining the bio-oil and the two-phase diluent in a mix-tee.
6. The method of Claim 1, the method comprising combining the bio-oil and the two-phase
20 diluent through a static-mixer.
7. The method of Claim 1, wherein combining the bio-oil and the two-phase diluent comprises directing the bio-oil through a quill within a pipe, wherein the pipe provides the two-phase diluent.
8. The method of Claim 1, wherein the bio-oil comprises poultry fats, poultry oil, vegetable
25 fats, rendered fats, rendered oils, restaurant grease, brown grease, yellow grease, used cooking oil, waste industrial frying oils, fish oils, fish fats, algal oils, microbial oils, or a combination of any two or more thereof.

9. The method of Claim 1, wherein the method produces a renewable diesel, wherein the renewable diesel has a carbon intensity of 30 gCO₂e/MJ or less according to California Air Resource Board CA-GREET3.0 model.
10. The method of any one of Claims 1-9, wherein the method further comprises a fouling of
5 the HDO reactor as evidenced by a pressure drop increase of no more than 10 psi during the service life of the catalyst.
11. The method of Claim 1, wherein contacting the diluted bio-oil with the catalyst bed provides a catalyst bed outlet product.
12. The method of Claim 1, wherein prior to combining the two-phase diluent and the bio-
10 oil, the method comprises adjusting the bio-oil temperature to be from 50 °F less than to 100 °F more than the water dew point.
13. The method of Claim 1, wherein prior to combining the two-phase diluent and the bio-oil, the process comprises measuring the two-phase diluent to determine the water dew point.