Syngas and Bio-Oil Upgrading

1st Brazil-U.S. Biofuels Short Course
Institute for Advanced Studies University of Sao Paulo, Brazil

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Outline

• Syngas Upgrading
  – Composition of syngas
  – Gas cleaning requirements
  – Contaminants in syngas and their elimination
  – Catalytic upgrading

• Bio-oil Upgrading
  – Why bio-oil is difficult to upgrade
  – Pathways to bio-oil conversion to transportation fuels
  – Description of bio-oil refining systems
Syngas

- Syngas consists of CO, H₂, CO₂, CH₄, and smaller quantities of higher hydrocarbons (the gas product from air-blown gasification contains as much as 50% molecular nitrogen and is known as producer gas)

<table>
<thead>
<tr>
<th>Composition of syngas (volume percent)</th>
<th>Hydrogen</th>
<th>Carbon Monoxide</th>
<th>Carbon Dioxide</th>
<th>Methane</th>
<th>Nitrogen</th>
<th>HHV (MJ/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>48</td>
<td>15</td>
<td>2</td>
<td>3</td>
<td>10.4</td>
<td></td>
</tr>
</tbody>
</table>
Pros and Cons of Syngas Upgrading

• Advantages (compared to biochemical platform)
  – Gasification tolerates relatively dirty biomass feedstock
  – Syngas is a uniform intermediate product
  – Proven method for “cracking the lignocellulosic nut”
  – Allows energy integration in biorefinery

• Disadvantages (compared to biochemical platform)
  – Gas cleaning technologies still under development
  – Synfuel processing occurs at high pressures
  – Economies of scale dictate large plant sizes

Fixed bed catalytic syngas reactor at Iowa State University
Contaminants found in Syngas

- Particulates
- Tar
- Alkali
- Sulfur
- Nitrogen

Gas Cleaning (some unit operations may be combined)

- Raw Syngas
- Particulate Removal
- Gasifier
- Oxygen/Steam
- Tar Elimination
- Alkali Removal
- Sulfur Removal
- Nitrogen Elimination
- Catalytic Synthesis
- Biofuel
Particulate Removal

- Requirements vary
- Must be below
  - 50 mg/Nm$^3$ for gas engines
  - 15 mg/Nm$^3$ (>5 µm) for turbines
  - 0.02 mg/Nm$^3$ for synthesis gas systems
Particulate Removal

• Primary Types
  – Cyclonic separators
  – Barrier filters
  – Electrostatic filters
Cyclonic Separators

- Based on centrifugal removal of particles in fast-moving gas stream
- Low pressure drop compared to amount of PM removed
- Dry collection and disposal
- Temperature and pressure limitation are dependent on the materials of construction
- No moving parts, few maintenance requirements and low operating costs
- Compact design
- Low capital cost
- Not effective below about 10 microns
Barrier Filters

- Porous metal or ceramic materials that allow the gas to pass and hold back particles
- Removing particles with diameters of 0.5 to 100 µm
- Usually after a cyclonic filter
Bag Filters

- Woven material intercepts small particles by impingement
- Efficiency increases as the filter cake thickness increases
- Work well for small diameter, even sub-micron, particles
- Temperature limitations to about 400 C
Electrostatic Filters

- Gas flows past high voltage electrode that imparts negative charges on the particles
- The gas then passes between positively charged plates that attracts the negatively charged particles
- Particles that accumulate on the positively charged plates are periodically removed by “rapping”
Wet Scrubbers/Oil Scrubbers

- Fine spray of water or oil washes particulate matter out of gas stream
- Mist eliminator prevents carry over of liquid droplets
- Also effective in removing tar and other contaminants
- Disadvantages:
  - Cools process stream
  - Produces wastewater problem
Tar

- Primary tar: released from pyolyzing biomass (same oxygenated compounds as found in bio-oil)
- Secondary tar: decomposition to phenolics and olefins
- Alkyl tertiary tar: aromatic hydrocarbons
- Condensed tertiary tar (poly aromatic hydrocarbons)

Evolution of Tar

Evolution of Tar

Tar Elimination

• Water or Oil Scrubbing
  – Integrated with particulate and ammonia removal

• Thermal Cracking
  – Tars decompose at sufficiently high temperature (typically 1000 °C or higher)
  – Refractory tars may be difficult to decompose
  – High temperatures encourage formation of carcinogenic polyaromatic hydrocarbons (PAH)
  – May require additional energy input to reach cracking temperature

• Catalytic Cracking
Catalytic Cracking

- Steam reforming process (800 - 900 °C)
  - Tar + H₂O → CO + H₂
  - Enhances heating value of syngas
- Dolomites and nickel-based catalysts extensively studied
- Catalytic cracking system often includes guard bed of dolomite ahead of main reactor
- Tertiary tars are more “recalcitrant” to cracking
- Coking (deposition of carbon deposits on catalyst surfaces) is a common problem
- Catalysts readily poisoned by sulfur
Strategies for Tar Removal

Alkali

- Alkali (metals) in biomass include potassium and to a lesser extent sodium
- Alkali responsible for sticky ash deposits (ash fouling), corrosion, and catalyst poisoning
- Alkali exists as both solid and vapor (can vaporize at temperatures as low as 600°C)

<table>
<thead>
<tr>
<th>Biomass feedstock</th>
<th>Alkali oxides (kg/GJ)</th>
<th>Fouling/slagging probability</th>
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</thead>
<tbody>
<tr>
<td>Yard waste</td>
<td>.50</td>
<td>Very high</td>
</tr>
<tr>
<td>Wood-Almond Shell mix</td>
<td>.40</td>
<td>Very high</td>
</tr>
<tr>
<td>Forest residuals</td>
<td>.22</td>
<td>Medium</td>
</tr>
<tr>
<td>Hybrid poplar</td>
<td>.17</td>
<td>Some</td>
</tr>
<tr>
<td>Red Oak</td>
<td>.09</td>
<td>Low</td>
</tr>
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</table>

Alkali Removal

- **Conventional Approach**
  - Gas stream cooled <600 °C to condense <5 µm particles of alkali salt
  - Use fine particulate filtration system to remove alkali particles
  - Energy inefficient
  - Corrosion can be a problem in filters

- **Advanced approach**
  - Alkali “getters” chemically adsorb alkali vapors
  - Fixed beds or pneumatically injected sprays of getters have been investigated
  - Inexpensive minerals like bauxite are preferred over regeneration
  - Chlorine can also be removed in this manner

<table>
<thead>
<tr>
<th>Alkali</th>
<th>Measured concentration without bauxite filter, ppmw</th>
<th>Measured concentration with bauxite filter, ppmw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na</td>
<td>28</td>
<td>0.07</td>
</tr>
<tr>
<td>K</td>
<td>11</td>
<td>0.58</td>
</tr>
</tbody>
</table>

Sulfur

• Biomass typically contains <0.1 wt% sulfur for wood and <0.4 wt% for crop residues
  – Results in low levels (<100 ppm) of H₂S in syngas

• Sulfur poisons many catalysts requiring its removal to <1 ppm for fuel cells and <0.1 ppm for synfuels manufacture
Sulfur Capture

- **Wet scrubbing**
- **Chemical gas treatments** absorb acid gases (both $\text{H}_2\text{S}$ and $\text{CO}_2$) in a liquid followed by pressure let down or steam stripping to recover the acid gases
  - Selexol – proprietary solvent absorbs acid gases at 2.07 to 13.8 MPa
  - Rectisol - cold methanol (−40 °C) absorbs acid gases at 2.76 to 6.89 MPa
  - Purisol - N-Methyl-2-Pyrrolidone is used to absorb acid gases
  - Amine Scrubbers – variety of amines absorb acid gases at 35 – 50 °C with heat regeneration
- **Solid sorbents**
  - Metal oxides can reversibly adsorb $\text{H}_2\text{S}$ at about 500 - 700 °C
  - These can be pelletized for fixed or moving beds or dispersed as fine powder into the syngas stream
  - Still under development
Nitrogen

- Nitrogen absorbed in roots of plants as $\text{NO}_3^-$ and $\text{NH}_4^+$
- Most converted to protein in leaves and young stems
- Gasification converts it to molecular nitrogen ($N_2$) or ammonia ($\text{NH}_3$) and smaller amounts of nitric oxide (NO)
- Amount of $\text{NH}_3$ and NO depend upon amount of nitrogen in biomass and processing conditions

Nitrogen Elimination

• Ammonia removal: Wet scrubbing
  – Appropriate when syngas is cooled
  – Acidic aqueous solution readily removes ammonia
  – Energy inefficient

• Ammonia destruction: Catalytic reforming
  – Appropriate when syngas is not cooled
  – Reduction chemistry: $2\text{NH}_3 \rightarrow \text{N}_2 + 3\text{H}_2$
  – Dolomite and nickel-based catalysts are effective at 800 °C while iron-based catalysts require temperatures of 900 °C
  – Can be accomplished during steam reforming of tar (same reactor)
Pathways to Syngas Products

- **Mixed Alcohols**
  - Alkali-doped ZnO/CeO2
  - Cu/ZnO/A12O3
  - MoS2

- **Fischer-Tropsch**
  - Formaldehyde
  - Oxidation
  - Co, Rh
  - WGS

Syngas (CO + H2)

- **Methanol**
  - MTBE
  - Acetic Acid
  - Direct Use
  - MTO
  - MTG
  - DME
  - M100
  - M85
  - DMFC

- **Ethanol**
  - Aldehydes
  - Alcohol

- **Waxes**
  - Diesel

- **Olefin**
  - Gasoline

- **i-C4**
  - Isosynthesis
  - ThO2 or ZrO2

- **NH3**
  - N2 over Fe/FeO (K2O, Al2O3, CaO)

- **H2**
  - Purify
Thermochemical Production of Hydrogen

Gas composition (dry basis, Vol %):

- H₂: 9
- CO: 14
- CO₂: 18
- CH₄: 5
- 20 g/Nm³ tars

Switchgrass and Air

- Dolomite 650°C, 900 h⁻¹
- NiO 800°C, 3000 h⁻¹
- Fe₂O₃ 400°C, 1500 h⁻¹
- CuO 200°C, 1200 h⁻¹

Guard Bed

- Catalyst: Dolomite
- Temperature: 650°C

Reformer

- Catalyst: NiO
- Temperature: 800°C

High Temp WGS

- Catalyst: Fe₂O₃
- Temperature: 400°C

Low Temp WGS

- Catalyst: CuO
- Temperature: 200°C

Reaction Conditions:
- Catalyst
- Reactor Temperature
- Space Velocity

Captures sulfur, chlorine, and tarry

Tar → CO + H₂

CO + H₂O → CO₂ + H₂
Catalysts for Hydrogen Production

- **Steam Reforming**
  - Converts methane, other light hydrocarbons, and tar to CO and H₂
  - Most steam reforming catalysts are 10-33 wt% NiO on a mineral support (alumina, cement, or magnesia)

- **Water-gas shift**
  - Increases hydrogen content of syngas while reducing carbon monoxide
  - CO + H₂O → CO₂ + H₂
  - Used for both hydrogen production and adjusting H₂:CO ratio for catalytic synthesis
  - Thermodynamically favored at low temperatures, which requires multiple WS reactors to achieve high hydrogen yields
  - High temperature catalyst (iron oxide, chromium oxide basis)
  - Low temperature catalyst (copper oxide in mixture with zinc oxide)

- **Promoter (potassium, lanthanum, ruthenium, and cerium)**
  - Prevents coking of the reforming catalysts
  - Increases steam gasification of solid carbon which reduces coke formation
Methanol Synthesis

• A high temperature, high-pressure, exothermic, equilibrium limited synthesis reaction

\[
\begin{align*}
CO + H_2 O & \rightarrow CO_2 + H_2 & \Delta H_r = -41.47 \text{ kJ / mol} \\
CO + 2H_2 & \rightarrow CH_3OH & \Delta H_r = -90.64 \text{ kJ / mol} \\
CO_2 + 3H_2 & \rightarrow CH_3OH + H_2O & \Delta H_r = -49.67 \text{ kJ / mol}
\end{align*}
\]

• Theoretical stoichiometric ratio \((H_2 – CO_2)/(CO+CO_2) = 2\)
• For kinetic reason and to control by-products, the ratio of higher than 2 is preferred
• Can achieve 99% conversion efficiency
• By-products of methanol production
  – \(\text{CH}_4, \text{DME, methyl formate, higher alcohols, and acetone}\)
• Reaction is about 100 times slower when \(\text{CO}_2\) is present
Methanol Reactors

- Cu/ZnO/Al$_2$O$_3$ operated at 220-275°C, 50-100 bar
- Adiabatic reactors usually contain multiple catalyst beds separated by gas cooling devices (direct heat exchange/injection of cooled, fresh or recycled syngas)
- Isothermal reactors operate like a heat exchange, continuously remove the heat of reaction
Mixed Alcohols

- Iron-based catalysts will convert syngas at 50 bar and 220-370°C to mixtures of alcohols (methanol, ethanol, 1-propanol, and 2-propanol)
- Selectivity to alcohols is over 95%, but production of pure ethanol is elusive
- Mixed alcohol synthesis has not been commercialized due to poor product selectivity and low syngas conversion.
- On a single pass, about 10% of syngas gets converted with most of the product composed of methanol.
Fisher-Tropsch Synthesis (FTS)

- Converts CO and H\(_2\) mixtures to a wide range of paraffins (saturated hydrocarbons), olefins (unsaturated hydrocarbons), and oxygenated products (alcohols, aldehydes, ketones, acids and esters)
- Water is a by-product
- Utilizes transition metal catalysts (iron or cobalt)
- Reactions are strongly exothermic, requiring large amounts of heat removal from synthesis reactors
FTS Reactions

• Operating regime affects product distribution
  • low temperature (200-240°C) yields more waxes (which can be cracked to diesel fuel)
  • high temperature (300-350°C) yields more gasoline
• FTS reaction is usually kept under 400°C to minimize CH₄ production
Chemistry behind FTS

- Basic reaction steps of FTS
  - Reactant (CO) adsorption on the catalyst surface
  - Chain initiation by CO dissociation followed by hydrogenation
  - Chain growth by insertion of additional CO molecules followed by hydrogenation
  - Chain termination
  - Product desorption from the catalyst surface
FTS reaction:

\[ CO + 2H_2 \rightarrow \cdots CH_2 \cdots + H_2O \quad \Delta H_r (227^\circ C) = -165kJ / mol \]

\[ CO + H_2O \rightarrow H_2 + CO_2 \ (Fe \ catalyzed \ reaction, \ Water - Gas \ Shift) \]

\[ 2CO + H_2 \rightarrow \cdots CH_2 \cdots + CO_2 \ (net \ overall \ FTS) \]

Synthesis reactions for specific FTS products:

\[ CO + 3H_2 \rightarrow CH_4 + H_2O \ (Methanation) \]

\[ nCO + (2n + 1)H_2 \rightarrow C_nH_{2n+2} + nH_2O \ (Paraffins) \]

\[ nCO + 2nH_2 \rightarrow C_nH_{2n} + nH_2O \ (Olefins) \]

\[ nCO + 2nH_2 \rightarrow C_nH_{2n+1}OH + (n - 1)H_2O \ (Alcohols) \]

\[ 2CO \rightarrow C_s + CO_2 \ (Boudouard \ reaction) \]

Carbon deposition on the catalyst surface causes catalyst deactivation
• FTS is kinetically controlled
• Chain polymerization kinetics model
  – Anderson-Shulz-Flory (ASF) model
  \[ W_n = n(1-\alpha)^2 \alpha^{n-1} \]
Catalysts

• In decreasing order of activity
  – Ru > Fe > Ni > Co > Rh > Pd > Pt

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni</td>
<td>Methanation catalyst</td>
</tr>
<tr>
<td>Ru</td>
<td>Produces high molecular weight products at low temperature</td>
</tr>
<tr>
<td>Fe</td>
<td>Has water-gas shift activity and strong tendency to produce carbons (deposit on the surface and deactivates the catalyst)</td>
</tr>
</tbody>
</table>
| Co | Improves carbon conversion to products
    Yields mainly straight chain hydrocarbons |
Fixed Bed Tubular Reactor

- 50% wax products
- Operate at 20-30 bar at 220-260°C
- Additional temperature control by high gas velocities and gas recycling
- Advantage
  - 70% conversion efficiency
  - Catalyst lifetime around 70-100 days
- Disadvantage
  - Catalyst removal is quite difficult
Fixed Fluidized Bed Reactor

• Replaced Sasol’s circulating fluidized bed reactor
• Advantage
  – Have better thermal efficiency,
    a less severe temperature gradient,
    and a lower pressure drop than
    Synthol reactor
  – Lower operating cost
  – Greater flexibility in product
    distribution
  – Scale up option
Low-Temperature Slurry Reactor

• Optimized high FT wax production with low methane production at low temperature

• Advantage
  – Better temperature control
  – Lower catalyst loading and attrition rates
  – Maintain higher average reaction temperature which lead to higher product conversion
  – 75% less expensive than complex tubular reactor

• Disadvantage
  – Difficult separation of catalyst from the FT waxes
Syngas Fermentation

- Traditional fermentations rely on carbohydrates as the source of carbon and energy in the growth of microbial biomass and the production of commercially valuable metabolites.
- Autotrophs use C_1 compounds as their sole source of carbon and hydrogen as their energy source.
- Unicarbonotrophs use C_1 compounds as their sole source of both carbon and energy.
- Among suitable C_1 compounds are CO, CO_2, and methanol (CH_3OH), all of which can be produced from thermochemical processing of biomass.
- Anaerobes offer the most energy efficient metabolic pathways: most of the chemical energy of the substrate appears in the products of fermentation.
- A number of microorganisms are able to utilize syngas for growth and production of hydrogen, alcohols, carboxylic acids, and esters.
Syngas Fermentation

• Advantages (compared to gasification biorefinery)
  – Biocatalysts tolerant to sulfur and chlorine contaminants
  – Flexibility in the pressures and CO/H$_2$ ratios employed
  – High selectivity in products produced
  – Genetic engineering can expand portfolio of products

• Disadvantages (compared to gasification biorefinery)
  – Low rates of gas-liquid exchange
  – Less developed technology

Questions about Syngas Cleaning and Upgrading?
What makes syngas upgrading inherently expensive?
Why do we worry about trace contaminants in syngas?
Seems like wet scrubbers can eliminate most contaminants – why are alternatives to this simple technology sought?
Can Fisher-Tropsch liquids supply both gasoline and aviation fuel?
Bio-Oil Upgrading
Problems with Bio-Oil

- Low heating value
- Immiscible with hydrocarbon fuels
- Solids content
- High viscosity
- Incomplete volatility
- Chemical instability
What has to be upgraded in bio-oil?

Pathways to Transportation Fuels

- Hydrodeoxygenation with hydrotreating catalysts
- Catalytic cracking over zeolites
- Steam reforming
- Gasification and catalytic upgrading of syngas
- Bio-oil fermentation
Hydrodeoxygenation (HDO)

• Catalysis-mediated removal of oxygen from bio-oil through reaction with hydrogen
  – Moderate temperatures (300 – 600 °C)
  – High partial pressures of hydrogen
  – Typically uses sulfided CoMo and NiMo-based catalysts similar to hydrotreating catalysts used to remove sulfur and nitrogen from petroleum
  – Water and saturated C-C bonds are formed

Model for deoxygenating lignin-derived compounds

[Diagram showing the conversion of guaiacol to cyclohexane through catechol and phenol]
Hydrodeoxygenation (HDO)

• Advantages
  – High carbon efficiency
  – Technology compatible with existing petroleum hydrotreating technology

• Disadvantages
  – High hydrogen demand
Catalytic cracking over zeolites

• Zeolites: Crystalline microporous materials with well-defined pore sizes of 0.5-1.2 nm.
  - High surface areas in pores
  - Active (usually acidic) sites give them high catalytic activity

• Bio-oil upgrading over zeolite occurs at 350-500 °C at atmospheric pressure.

• Reactions include cracking, dehydration, deoxygenation, polymerization, and aromatization.
Bio-Oil Upgrading Results for Different Kinds of Zeolite Catalysts

<table>
<thead>
<tr>
<th>catalyst properties</th>
<th>HZSM-5</th>
<th>silica–alumina (SiO₂–Al₂O₃ ratio 0.14)</th>
<th>SAPO-5</th>
<th>SAPO-11</th>
<th>MgAPO-36</th>
</tr>
</thead>
<tbody>
<tr>
<td>pore size (nm)</td>
<td>0.54</td>
<td>3.15</td>
<td>0.80</td>
<td>0.56</td>
<td>0.75</td>
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<tr>
<td>BET surface area (m²/g)</td>
<td>329</td>
<td>321</td>
<td>330</td>
<td>205</td>
<td>196</td>
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<tr>
<td>acid area (cm²/g)⁶</td>
<td>224.9</td>
<td></td>
<td>125.5</td>
<td>76.0</td>
<td>15.5</td>
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<tr>
<td>product yields (wt % of feed)</td>
<td></td>
<td></td>
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<tr>
<td>organic liquid product</td>
<td>33.6</td>
<td>24.9</td>
<td>22.2</td>
<td>19.9</td>
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<td>gas</td>
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<td>10.3</td>
<td>12.2</td>
<td>10.1</td>
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<tr>
<td>coke + char⁷</td>
<td>20.5–30.2</td>
<td>40</td>
<td>30.0</td>
<td>25.5</td>
<td>38.7</td>
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<tr>
<td>tar⁸</td>
<td>0–4.1</td>
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<td>9.5</td>
<td>11.9</td>
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<td>aqueous fraction</td>
<td></td>
<td></td>
<td>25.0</td>
<td>24.2</td>
<td>26.3</td>
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<td>composition organic liquid product (wt %)</td>
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<tr>
<td>total hydrocarbons</td>
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<td>51.0</td>
<td>56.8</td>
<td>51.6</td>
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<td>aromatics</td>
<td>85.9e</td>
<td>2.1</td>
<td>27.5</td>
<td>29.1</td>
<td>26.7</td>
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<tr>
<td>aliphatics</td>
<td>18.6</td>
<td>43.5</td>
<td>23.5</td>
<td>24.4</td>
<td>23.4</td>
</tr>
</tbody>
</table>

Products of Zeolite Upgrading
(Model Compounds)

Catalytic cracking over zeolites

• Advantages
  – No hydrogen is used
  – Atmospheric operation is possible

• Disadvantages
  – Poor hydrocarbon yields
  – High coke yields
Fluidized Catalytic Cracker (FCC)

Coke burned off catalyst particles

Feedstock cracked in presence of catalyst particles
Steam Reforming

• Reaction of bio-oil with steam at 600 – 800 °C over Ni-based catalyst to produce hydrogen-rich syngas

• Important parameters
  – Temperature
  – Steam-to-carbon ratio
  – Catalyst-to-feed ratio

• Coking can be a major problem
Aqueous Phase Processing (APP)

- Furfural (from 5-carbon sugars) and 5-hydroxymethyl furfural (from 6-carbon sugars) are reacted in liquid water with heterogeneous (solid) catalyst at low temperatures (200 – 260°C) at 10-50 bar.
- Originally developed for aqueous phase reforming (APR) of carbohydrate into hydrogen.
- Hydrocarbon formation is encouraged by addition of metal (Pt or Pd) and acid (SiO2-Al2O3) sites to catalyze dehydration and hydrogenation reactions (ADP/H), respectively.
- Hydrogen for ADP/H is provided by APR.
- Bio-oil upgrading via APP is under development.
Aqueous Phase Processing to Hydrocarbons

Biomass → Acid Hydrolysis → Acid Dehydration → Aldol Condensation → 4-PD/H → Alkanes

+ 6 H₂O → 6 CO₂ + 12 H₂

Sugars → Aqueous-Phase Reforming → H₂ → H₂O
Aqueous Phase Processing to Hydrocarbons

• Advantages
  – Highly selective
  – Highly energy efficient

• Disadvantages
  – 5-hydroxymethyl furfural not efficiently produced from glucose
  – Hexane is major product, which is too volatile to be major fuel component
  – Has not been sufficiently developed to use real biomass feedstocks
Bio-Oil Gasification

• Bio-oil and char slurried together to recover 90% of the original biomass energy
• Slurry transported to central processing site where it is gasified in an entrained flow gasifier to syngas
• Syngas is catalytic processed into green diesel (F-T liquids)
Bio-Oil Hydrocracking

- Directly converts biomass into liquid bio-oil (lignin, carbohydrate derivatives, and water) and char
- Bio-oil catalytically converted into hydrocarbon fuel (green diesel)
Questions about Bio-Oil Upgrading?
Why does bio-oil need to be upgraded before it is used as transportation fuel?
How does hydrodeoxygenation fundamentally different from catalytic cracking?
If bio-oil and syngas are both “pyrolytic intermediates,” why would we consider gasifying bio-oil to produce biofuels?
What are some of the advantages of syngas fermentation compared to catalytic upgrading of syngas?