CLAIMS

1. A method for upgrading pyrolysis oil, the method comprising:

contacting a pyrolysis oil feed with hydrogen in the presence of a mixed metal oxide catalyst and a secondary catalyst in a first fixed-bed reactor, where:

the pyrolysis oil feed comprises multi-ring aromatic compounds comprising greater than or equal to sixteen carbon atoms;

the first fixed-bed reactor comprises a first catalyst bed and a second catalyst bed downstream from the first catalyst bed;

the first catalyst bed comprises the mixed metal oxide catalyst;

the mixed metal oxide catalyst comprises a plurality of MMO particles and each of the plurality of MMO particles comprises Fe_2O_3, ZrO_2, CeO_2, and Al_2O_3,

the second catalyst bed comprises a secondary catalyst;

the method comprises contacting the pyrolysis oil feed and the hydrogen with the mixed metal oxide catalyst in the first catalyst bed and then with the secondary catalyst downstream of the mixed metal oxide catalyst in the second catalyst bed in the first fixed-bed reactor; and

contacting the pyrolysis oil feed with hydrogen in the presence of the mixed metal oxide catalyst in the first catalyst bed and the secondary catalyst in the secondary catalyst bed in the first fixed-bed reactor causes at least a portion of the multi-ring aromatic compounds in the pyrolysis oil feed to react to produce an intermediate stream comprising di-aromatic compounds, tri-aromatic compounds, or combinations thereof;

contacting the intermediate stream with hydrogen in the presence of a mesoporous supported metal catalyst in a second fixed-bed reactor, where:

the mesoporous supported metal catalyst comprises nickel and tungsten impregnated onto a mesoporous support comprising a large pore alumina, a binder, and at least one zeolite;

contacting the intermediate stream with the hydrogen in the presence of the mesoporous supported metal catalyst causes at least a portion of the di-aromatic compounds and/or tri-aromatic compounds in the intermediate stream to react to produce a second reactor effluent comprising aromatic compounds having six to eight carbon atoms.

2. The method of claim 1, further comprising mixing a heavy pyrolysis oil from a naphtha steam cracker with a light aromatic stream upstream of the first fixed-bed reactor to produce the pyrolysis oil feed and passing the pyrolysis oil feed to the first fixed-bed reactor.

3. The method of claim 2, wherein the pyrolysis oil feed comprises from 75 wt. % to 85 wt. % of the heavy pyrolysis oil and from 15 wt. % to 25 wt. % of the light aromatic stream.

4. The method of claim 1 wherein the secondary catalyst comprises:
from 18.5 wt. % to 21.5 wt. % of Al_2O_3,
from 36.5 wt. % to 39.5 wt. % of SiO_2,
from 9.2 wt. % to 10.2 wt. % of ZrO_2,
from 10.5 wt. % to 11.5 wt. % of NiO, and
from 18.5 wt. % to 21.5 wt. % of WO_3, on the basis of the total metal oxide weight of the secondary catalyst.

5. The method of claim 1, in which each of the MMO particles comprises:
from 60 wt.% to 95 wt.% iron oxide;
from 1 wt.% to 20 wt.% zirconium oxide;
from 0.1 wt.% to 10 wt.% cerium oxide; and
from 1 wt.% to 20 wt.% aluminum oxide,
where the weight percentages are based on the total weight of the MMO particles in the mixed metal oxide catalyst.

6. The method of claim 1, in which:
the mixed metal oxide catalyst further comprises a binder material; and
the mixed metal oxide catalyst is in the form of pellets.

7 The method of claim 1, in which the alumina of the mesoporous supported metal catalyst comprises large pore alumina with an average pore size at least 5 nm.

8. The method of claim 1, in which the zeolite of the mesoporous supported metal catalyst comprises both nano zeolite beta and USY zeolite.

9. The method of claim 1, wherein:

the mesoporous supported metal catalyst comprises from 2 wt. % to 10 wt. % of the large pore alumina, from 10 wt. % to 20 wt. % of a binder material, from 40 wt. % to 60 wt. % of the zeolite, from 4 wt. % to 8 wt. % of the nickel oxide, and from 20 wt. % to 30 wt. % of the tungsten oxide, on the basis of the total weight of the mesoporous supported metal catalyst;

the zeolite comprises a USY zeolite and a nano-sized zeolite beta; and

a weight ratio of USY:nano-sized zeolite beta is from 1.25 to 1.75.

10. The method of claim 1, in which the pyrolysis oil feed comprises greater than or equal to 30 weight percent (wt.%) multi-ring aromatic compounds having greater than or equal to sixteen carbon atoms based on the total weight of the pyrolysis oil in the pyrolysis oil feed.

11. The method of claim 1, comprising:

contacting the pyrolysis oil feed with hydrogen in the presence of the mixed metal oxide catalyst in the first fixed-bed reactor at one or more of the following reaction conditions: (a) a temperature of from 300 degrees Celsius (°C) to 500 °C; (b) a pressure of from 1 megapascal (MPa) (10 bar) to 20 MPa (200 bar); (c) a volume ratio of hydrogen to the pyrolysis oil feed of from 500 to 1500, or combinations of these reaction conditions; and

contacting the intermediate stream with hydrogen in the presence of the mesoporous supported metal catalyst in the second fixed-bed reactor at one or more of the following reaction conditions: (a) a temperature of from 300 °C to 500 °C (b) a pressure of from 1 MPa (10 bar) to 20 MPa (200 bar), or combinations of these reaction conditions.

12. The method of claim 1, in which contacting the pyrolysis oil feed with hydrogen in the presence of the mixed metal oxide catalyst and contacting the intermediate stream with hydrogen in the presence of the mesoporous zeolite supported metal catalyst result in a yield of greater than or equal to 45 wt.% of the aromatic compounds having six to eight carbons based on the total weight of pyrolysis oil in the pyrolysis oil feed.

13. The method of claim 1, further comprising:

steam cracking a naphtha stream to produce one or more product streams and a heavy pyrolysis oil, passing the heavy pyrolysis oil to the first fixed-bed reactor as at least a portion of the pyrolysis oil feed; or

steam cracking a hydrocarbon gas to produce at least one light olefin stream and a light pyrolysis oil, and

passing the light pyrolysis oil to the first fixed-bed reactor as at least a portion of the pyrolysis oil feed.

14. A system for upgrading pyrolysis oil, the system comprising:

a first fixed-bed reactor comprising a first catalyst bed comprising a mixed metal oxide catalyst and a second catalyst bed comprising a secondary catalyst, where:

the first fixed-bed reactor is operable to contact a pyrolysis oil feed with hydrogen in the presence of the mixed metal oxide catalyst in the first catalyst bed and the secondary catalyst in the second catalyst bed to produce an intermediate stream comprising light aromatic compounds that include mono-aromatic compounds, di-aromatic compounds, tri-aromatic compounds, or both, the mixed metal oxide catalyst comprising a plurality of catalyst particles and each of the plurality of catalyst particles comprises Fe_2O_3, ZrO_2, CeO_2, and Al_2O_3;

a second fixed-bed reactor downstream of the first fixed-bed reactor and comprising a mesoporous supported metal catalyst, where:

the second fixed-bed reactor is operable to contact the intermediate stream with hydrogen in the presence of the mesoporous supported metal catalyst to produce a second reactor effluent comprising aromatic compounds having six to eight carbon atoms; and

the mesoporous supported metal catalyst comprises nickel and tungsten impregnated onto a mesoporous support comprising alumina and at least one zeolite.

15. The system of claim 14, in which one or both of:

the catalyst particles of the mixed metal oxide catalyst each comprise:

from 60 wt.% to 95 wt.% iron oxide,

from 1 wt.% to 20 wt.% zirconium oxide,

from 0.1 wt.% to 10 wt.% cerium oxide, and

from 1 wt.% to 20 wt.% aluminum oxide, where the weight percentages are based on the total metal oxide weight of the catalyst particles in the mixed metal oxide catalyst; and

the secondary catalyst comprises from 18.5 wt. % to 21.5 wt. % of Al2O3, from 36.5 wt. % to 39.5 wt. % of SiO2, from 9.2 wt. % to 10.2 wt. % of ZrO2, from 10.5 wt. % to 11.5 wt. % of NiO, and from 18.5 wt. % to 21.5 wt. % of WO3, on an oxide basis and on the basis of the total weight of secondary catalyst.