CLAIMS

What is claimed is:

1. A membrane-integrated hydration reactor operable to produce an associated alcohol product from an olefin using water, the membrane-integrated hydration reactor comprising:

a solid acid olefin hydration catalyst operable to convert the olefin into an associated alcohol using water at olefin hydration process conditions;

a hydrophilic membrane having a feed side and a permeate side, operable to selectively pervaporate water one-way from the feed side to the permeate side at olefin hydration process conditions, forming a pervaporated water product, and to prevent the pervaporation of associated alcohol and permeation of the olefin at olefin hydration conditions;

a production zone containing the solid acid olefin hydration catalyst, operable to both receive an olefin feed containing the olefin and a water feed containing the water such that the olefin and the water intimately intermingle in the presence of the solid acid olefin hydration catalyst contained in the production zone and to form a production zone product mixture comprising the associated alcohol and any unreacted water and pass the production zone product mixture to an associated separations zone; and

the associated separations zone containing the hydrophilic membrane, fluidly coupling to the production zone such that the production zone directs the production zone product mixture to the feed side of the hydrophilic membrane, and is operable to form and produce both the associated alcohol product and the pervaporated water product from the production zone product mixture.

2. The membrane-integrated hydration reactor of claim 1 where the olefin is a single isomer of butene and the associated alcohol is a single isomer of butanol.

3. The membrane-integrated hydration reactor of claim 1 where the olefin is a mixture of butene isomers and the associated alcohol is a mixture of butanol isomers.

4. The membrane-integrated hydration reactor of claim 1 where the olefin is a mixture of lower-carbon olefins and the associated alcohol is a mixture of lower-carbon alcohols.

5. The membrane-integrated hydration reactor of any of the claims 1 to 4 where the production zone and the associated separations zone overlap within the reactor.

6. The membrane-integrated hydration reactor of any of the claims 1 to 5 where the solid acid olefin hydration catalyst is a structured catalyst bed.

7. The membrane-integrated hydration reactor of any of the claims 1 to 5 where the solid acid olefin hydration catalyst is integrated with the feed side surface of the hydrophilic membrane.

8. The membrane-integrated hydration reactor of any of the claims 1 to 7 where the hydrophilic membrane comprises an inorganic material.

9. The membrane-integrated hydration reactor of any of the claims 1 to 8 where the hydrophilic membrane comprises a polymeric material.

10. The membrane-integrated hydration reactor of any of the claims 1 to 9 further comprising an internal condenser operable to condense into a liquid the pervaporated water product on the permeate side of the hydrophilic membrane.

11. The membrane-integrated hydration reactor of any of the claims 1 to 10 where the membrane-integrated hydration reactor is operable to maintain separate operating conditions between the production zone and the associated separations zone.

12. The membrane-integrated hydration reactor of any of the claims 1 to 11 where the membrane-integrated hydration reactor comprises more than one production zone and more than one associated separations zones.

13. The membrane-integrated hydration reactor of claim 12 where the more than one production zones and the more than one associated separations zones are alternating in series and fluidly couple to permit one-way fluid communications through the alternating series of production zones and associated separations zones, where the fluid of communication is water.

14. The membrane-integrated hydration reactor of claim 13 such that in the alternating series of fluidly coupled more than one production zones and more than one associated separations zones a first production zone is operable to communicate fluid one-way to all of the remaining production zones and all of the separations zones and such that a last separations zone in the alternating series is operable to receive fluid communicated one-way from all of the production zones and all of the remaining separations zones.

15. The membrane-integration hydration reactor of claim 13 or claim 14 such that in the alternating series of fluidly coupled more than one production zones and more than one

associated separations zones a first production zone is in direct fluid contact only with one associated separations zone and a last separations zone in the alternating series is in direct fluid contact only with one production zone, the other production zones being in direct fluid contact with more than one separations zones and the other separations zones being in direct fluid contact with more than one production zones.

16. The membrane-integrated hydration reactor of any of the claims 13 to 15 where the membrane-integrated hydration reactor is operable to maintain separate operating conditions between a first set of production and associated separations zones and a second set of production and associated separations zones, where the first associated separations zone is fluidly coupled to and in one-way fluid communications with the second production zone.

17. A method of olefin hydration in a membrane-integrated hydration reactor of any of the previous claims, the method of olefin hydration comprising the steps of:

introducing an olefin feed composition into the production zone of the membrane-integrated hydration reactor, where the olefin feed composition comprises at least one isomer of butene,

introducing water into the production zone of the membrane-integrated hydration reactor,

operating the membrane-integrated hydration reactor at olefin hydration process conditions such that the associated alcohol forms from the olefin feed composition using water in the presence of a solid acid olefin hydration catalyst in the production zone, the production zone product mixture forms from the mixing of the associated alcohol and any unreacted water in the production zone, the production zone product mixture passes from the production zone to the associated separations zone, and the associated separations zone selectively removes any unreacted water from the production zone product mixture, forming both the associated alcohol product and a pervaporated water product.

18. The method of olefin hydration of claim 17 where the olefin feed composition comprises only a single isomer of butene and the associated alcohol product comprises only a single isomer of butanol.

19. The method of olefin hydration of claim 17 or claim 18 where the olefin feed composition comprises at least 5 weight percent iso-butene.

20. The method of olefin hydration of claim 17 where the olefin feed composition comprises mixed butenes and the associated alcohol product comprises mixed butanols.

21. The method of olefin hydration of claim 17 where the olefin feed composition comprises lower-carbon mixed olefins and the associated alcohol product comprises lower-carbon mixed alcohols.

22. The method of olefin hydration of any one of the claims 17 to 21 further comprising the step of pre-combining the olefin feed composition and water before introducing the combination into the production zone.

23. The method of olefin hydration of any one of the claims 17 to 22 where the stoichiometric ratio of water to olefins in the olefin feed composition introduced into the membrane-integrated hydration reactor is in the range of from 1:1 to 10:1.

24. The method of olefin hydration of any one of the claims 17 to 23 where the stoichiometric ratio of water to olefins in the olefin feed composition introduced into a first production zone is different than the stoichiometric ratio of water to olefins in the olefin feed composition introduced into a second production zone.

25. The method of olefin hydration of any one of the claims 17 to 24 where the olefin hydration process conditions in the production zone includes a stoichiometric ratio of water to olefins in a range of from 1:1 to 10:1.

26. The method of olefin hydration of any one of the claims 17 to 25 where the olefin hydration process conditions in the production zone includes a pressure in a range of from 8 bars to 70 bars.

27. The method of olefin hydration of any one of the claims 17 to 26 where the olefin hydration process conditions in the production zone includes a temperature in a range of from 50 °C to 150 °C.

28. The method of olefin hydration of any one of the claims 17 to 27 where the olefin hydration process conditions in the separations zone includes a pressure differential between the feed side and the permeate side of the hydrophilic membrane in a range of from 8 bars to 70 bars differential.

29. The method of olefin hydration of any one of the claims 17 to 28 where the olefin hydration process conditions in the separations zone includes a pressure on the permeate side of the hydrophilic membrane of less than atmospheric pressure.

30. The method of olefin hydration of any one of the claims 17 to 29 where the membrane-integrated hydration reactor is operated such that a first set of production and associated separations zones has a first set of olefin hydration process conditions and a second set of set of production and associated separations zones has a second set of olefin hydration process conditions, the first set of zones fluidly coupled to and in one-way fluid communication with the second set of production and associated separations zones.

31. The method of olefin hydration of any one of the claims 17 to 30 where the membrane-integrated hydration reactor is operated such that the associated alcohol product is substantially free of water by weight.

32. The method of olefin hydration of any one of the claims 17 to 31 where the membrane-integrated hydration reactor is operated such that the associated alcohol product contains less than or equal to 0.5 weight percent water of the total product.

33. The method of olefin hydration of any one of the claims 17 to 32 where the membrane-integrated hydration reactor is operated such that the associated alcohol product contains less than or equal to 100 parts-per-million by volume butenes in the product.

34. The method of olefin hydration of any one of the claims 17 to 33 further comprising the step of producing the pervaporated water product from the associated separations zone such that it is introduced into a fluidly coupled production zone.

35. The method of olefin hydration of any one of the claims 17 to 34 further comprising the step of producing the pervaporated water product from the associated separations zone such that it is directly introduced into a fluidly coupled production zone, the associated separations zone in one-way fluid communication with and fluidly coupled to the fluidly coupled production zone through the permeate side of the hydrophilic membrane.

CLAIMS

1. A membrane-integrated hydration reactor operable to produce an associated alcohol product from an olefin using water, the membrane-integrated hydration reactor comprising:

a solid acid olefin hydration catalyst operable to convert the olefin into an associated alcohol using water at olefin hydration process conditions;

a hydrophilic membrane having a feed side and a permeate side, operable to selectively pervaporate water one-way from the feed side to the permeate side at olefin hydration process conditions, forming a pervaporated water product, and to prevent the pervaporation of associated alcohol and permeation of the olefin at olefin hydration conditions;

a production zone containing the solid acid olefin hydration catalyst, operable to both receive an olefin feed containing the olefin and a water feed containing the water such that the olefin and the water intimately intermingle in the presence of the solid acid olefin hydration catalyst contained in the production zone and to form a production zone product mixture comprising the associated alcohol and any unreacted water and pass the production zone product mixture to an associated separations zone; and

the associated separations zone containing the hydrophilic membrane, fluidly coupling to the production zone such that the production zone directs the production zone product mixture to the feed side of the hydrophilic membrane, and is operable to form and produce both the associated alcohol product and the pervaporated water product from the production zone product mixture.

2. The membrane-integrated hydration reactor of claim 1 where the solid acid olefin hydration catalyst is operable to convert a single isomer of butene into a single isomer of butanol at olefin hydration process conditions.

3. The membrane-integrated hydration reactor of claim 1 where the solid acid olefin hydration catalyst is operable to convert a mixture of butene isomers into a mixture of butanol isomers at olefin hydration process conditions.

4. The membrane-integrated hydration reactor of claim 1 where the solid acid olefin hydration catalyst is operable to convert a mixture of lower-carbon olefins into a mixture of lower-carbon alcohols at olefin hydration process conditions.

5. The membrane-integrated hydration reactor of any of the claims 1 to 4 where the production zone and the associated separations zone overlap within the reactor.

6. The membrane-integrated hydration reactor of any of the claims 1 to 5 where the solid acid olefin hydration catalyst is a structured catalyst bed.

7. The membrane-integrated hydration reactor of any of the claims 1 to 5 where the solid acid olefin hydration catalyst is integrated with the feed side surface of the hydrophilic membrane.

8. The membrane-integrated hydration reactor of any of the claims 1 to 7 where the hydrophilic membrane comprises an inorganic material.

9. The membrane-integrated hydration reactor of any of the claims 1 to 8 where the hydrophilic membrane comprises a polymeric material.

10. The membrane-integrated hydration reactor of any of the claims 1 to 9 further comprising an internal condenser operable to condense into a liquid the pervaporated water product on the permeate side of the hydrophilic membrane.

11. The membrane-integrated hydration reactor of any of the claims 1 to 10 where the membrane-integrated hydration reactor is operable to maintain separate operating conditions between the production zone and the associated separations zone, where the production zone and the associated separations zone are coupled together but do not contact each other.

12. The membrane-integrated hydration reactor of any of the claims 1 to 11 where the membrane-integrated hydration reactor comprises more than one production zone and more than one associated separations zones.

13. The membrane-integrated hydration reactor of claim 12 where the more than one production zones and the more than one associated separations zones are alternating in series and fluidly couple to permit one-way fluid communications through the alternating series of production zones and associated separations zones, where the fluid of communication is water.

14. The membrane-integrated hydration reactor of claim 13 such that in the alternating series of fluidly coupled more than one production zones and more than one associated separations zones a first production zone is operable to communicate fluid one-way to all of the remaining production zones and all of the separations zones and such that a last separations zone in the alternating series is operable to receive fluid communicated one-way from all of the production zones and all of the remaining separations zones.

15. The membrane-integration hydration reactor of claim 13 or claim 14 such that in the alternating series of fluidly coupled more than one production zones and more than one associated separations zones a first production zone is in direct fluid contact only with one associated separations zone and a last separations zone in the alternating series is in direct fluid contact only with one production zone, the other production zones being in direct fluid contact with more than one

separations zones and the other separations zones being in direct fluid contact with more than one production zones.

16. The membrane-integrated hydration reactor of any of the claims 13 to 15 where the membrane-integrated hydration reactor is operable to maintain separate operating conditions between a first set of production and associated separations zones and a second set of production and associated separations zones, where the first associated separations zone is fluidly coupled to and in one-way fluid communications with the second production zone, through a hydrophilic membrane of the first associated separations zone.

17. A method of olefin hydration in a membrane-integrated hydration reactor of any of the previous claims, the method of olefin hydration comprising the steps of:

introducing an olefin feed composition into the production zone of the membrane-integrated hydration reactor, where the olefin feed composition comprises at least one isomer of butene,

introducing water into the production zone of the membrane-integrated hydration reactor,

operating the membrane-integrated hydration reactor at olefin hydration process conditions such that the associated alcohol forms from the olefin feed composition using water in the presence of a solid acid olefin hydration catalyst in the production zone, the production zone product mixture forms from the mixing of the associated alcohol and any unreacted water in the production zone, the production zone product mixture passes from the production zone to the associated separations zone, and the associated separations zone selectively removes any unreacted water from the production zone product mixture, forming both the associated alcohol product and a pervaporated water product.

18. The method of olefin hydration of claim 17 where the olefin feed composition comprises only a single isomer of butene and the associated alcohol product comprises only a single isomer of butanol.

19. The method of olefin hydration of claim 17 or claim 18 where the olefin feed composition comprises at least 5 weight percent iso-butene.

20. The method of olefin hydration of claim 17 where the olefin feed composition comprises mixed butenes and the associated alcohol product comprises mixed butanols.

21. The method of olefin hydration of claim 17 where the olefin feed composition comprises lower-carbon mixed olefins and the associated alcohol product comprises lower-carbon mixed alcohols.

22. The method of olefin hydration of any one of the claims 17 to 21 further comprising the step of pre-combining the olefin feed composition and water before introducing the combination into the production zone.

23. The method of olefin hydration of any one of the claims 17 to 22 where the stoichiometric ratio of water to olefins in the olefin feed composition introduced into the membrane-integrated hydration reactor is in the range of from 1:1 to 10:1.

24. The method of olefin hydration of any one of the claims 17 to 23 where the stoichiometric ratio of water to olefins in the olefin feed composition introduced into a first production zone is different than the stoichiometric ratio of water to olefins in the olefin feed composition introduced into a second production zone.

25. The method of olefin hydration of any one of the claims 17 to 24 where the olefin hydration process conditions in the production zone includes a stoichiometric ratio of water to olefins in a range of from 1:1 to 10:1.

26. The method of olefin hydration of any one of the claims 17 to 25 where the olefin hydration process conditions in the production zone includes a pressure in a range of from 8 bars to 70 bars.

27. The method of olefin hydration of any one of the claims 17 to 26 where the olefin hydration process conditions in the production zone includes a temperature in a range of from 50 °C to 150 °C.

28. The method of olefin hydration of any one of the claims 17 to 27 where the olefin hydration process conditions in the separations zone includes a pressure differential between the feed side and the permeate side of the hydrophilic membrane in a range of from 8 bars to 70 bars differential.

29. The method of olefin hydration of any one of the claims 17 to 28 where the olefin hydration process conditions in the separations zone includes a pressure on the permeate side of the hydrophilic membrane of less than atmospheric pressure.

30. The method of olefin hydration of any one of the claims 17 to 29 where the membrane-integrated hydration reactor is operated such that a first set of production and associated separations zones has a first set of olefin hydration process conditions and a second set of set of production and associated separations zones has a second set of olefin hydration process conditions, the first set of zones fluidly coupled to and in one-way fluid communication with the second set of production and associated separations zones.

31. The method of olefin hydration of any one of the claims 17 to 30 where the membrane-integrated hydration reactor is operated such that the associated alcohol product is substantially free of water by weight.

32. The method of olefin hydration of any one of the claims 17 to 31 where the membrane-integrated hydration reactor is operated such that the associated alcohol product contains less than or equal to 0.5 weight percent water of the total product.

33. The method of olefin hydration of any one of the claims 17 to 32 where the membrane-integrated hydration reactor is operated such that the associated alcohol product contains less than or equal to 100 parts-per-million by volume butenes in the product.

34. The method of olefin hydration of any one of the claims 17 to 33 further comprising the step of producing the pervaporated water product from the associated separations zone such that it is introduced into a fluidly coupled production zone.

35. The method of olefin hydration of any one of the claims 17 to 34 further comprising the step of producing the pervaporated water product from the associated separations zone such that it is directly introduced into a fluidly coupled production zone, the associated separations zone in one-way fluid communication with and fluidly coupled to the fluidly coupled production zone through the permeate side of the hydrophilic membrane.