~~What is claimed is:~~

~~1. An upflow single shell open interstage reactor comprising:~~

~~a) a first shell-and-tube reaction stage comprising a plurality of reaction tubes, wherein the reaction tubes of the first reaction stage comprise a first catalyst;~~

~~b) an interstage heat exchanger;~~

~~c) an open interstage region; and~~

~~d) a second shell-and-tube reaction stage comprising a plurality of reaction tubes, wherein the reaction tubes of the second reaction stage comprise a second catalyst;~~

~~wherein said interstage heat exchanger is positioned between said first reaction stage and said open interstage region, and~~

~~wherein said reactor is configured for upflow operation.~~

~~2. The reactor of claim 1, wherein said interstage heat exchanger is a shell-and-tube heat exchanger and comprises a plurality of interstage heat exchanger tubes.~~

~~3. The reactor of claim 2, wherein said interstage heat exchanger tubes are coaxially continuous with the reaction tubes of the first reaction stage.~~

~~4. The reactor of claim 2, wherein said interstage heat exchanger tubes comprise a catalyst retaining device.~~

~~5. The reactor of claim 4, wherein said catalyst retaining device is capable of inducing turbulence within the said interstage heat exchanger tubes.~~

~~6. The reactor of claim 2, wherein said interstage heat exchanger tubes comprise high void fraction, turbulence-inducing inserts.~~

~~7. The reactor of claim 6, wherein said inserts have a void fraction of at least 85%.~~

8. The reactor of claim 1, wherein said first reaction stage further comprises a first shellside coolant and said second reaction stage further comprises a second shellside coolant.

9. The reactor of claim 8, wherein said first shellside coolant is controlled independently of said second shellside coolant.

10. The reactor of claim 2, wherein said interstage heat exchanger further comprises a shellside heat exchanger coolant.

11. The reactor of claim 10, wherein said first reaction stage further comprises a first shellside coolant that is controlled independently of said heat exchanger coolant.

12. The reactor of claim 1, wherein said open interstage region is at least partially filled with at least one inert material.

13. The reactor of claim 12, wherein said inert material has a surface area to bulk volume ratio of at least 78.7 m^2/cubic m (24 ft^2/ cubic foot).

14. The reactor of claim 12, wherein said inert material is present in an amount sufficient to provide at least 2790 m^2 (30,000 ft^2) of total surface area.

15. The reactor of claim 1, wherein the reaction tubes of the first reaction stage have a different cross-sectional area than the reaction tubes of the second reaction stage.

16. The reactor of claim 15, wherein the reaction tubes of the second reaction stage have a cross-sectional area at least 25% greater than the cross-sectional area of the reaction tubes of the first reaction stage.

17. The reactor of claim 16, wherein the reaction tubes of the second reaction stage have a cross-sectional area at least 50% greater than the cross-sectional area of the reaction tubes of the first reaction stage.

18. The reactor of claim 1, wherein the reaction tubes of the second reaction stage have an internal diameter greater than 22.3 mm (0.878 in).

19. The reactor of claim 18, wherein the reaction tubes of the second reaction stage have an internal diameter greater than 25.4 mm (1 in).

20. The reactor of claim 1, wherein said open interstage region comprises a supplemental oxidant supply line.

21. The reactor of claim 20, wherein said open interstage region further comprises a supplemental oxidant mixing assembly.

22. The reactor of claim 21, wherein said supplemental oxidant mixing assembly comprises a venturi mixer.

23. The reactor of claim 20, wherein said supplemental oxidant supply line comprises an oxidant heat exchanger.

24. The reactor of claim 1, further comprising inlet and outlet reactor heads, wherein at least one of said inlet reactor head and said outlet reactor head is removable.

25. The reactor of claim 1, wherein at least one region chosen from the first reaction stage, the interstage heat exchanger, and the second reaction stage is configured for co-current coolant circulation.

26. The reactor of claim 1, wherein at least one region chosen from the first reaction stage, the interstage heat exchanger, and the second reaction stage is configured for counter-current coolant circulation.

27. The reactor of claim 1, wherein the second reaction stage comprises at least 22,000 reaction tubes.

28. The reactor of claim 27, wherein the second reaction stage comprises at least 30,000 reaction tubes.

29. The reactor of claim 1, wherein the number of reaction tubes in the first reaction stage is approximately equal to the number of reaction tubes in the second reaction stage.

30. The reactor of claim 1, wherein the number of reaction tubes in the first reaction stage is different than the number of reaction tubes in the second reaction stage.

31. The reactor of claim 1, wherein the reaction tubes in the second reaction stage are no greater than 4,500 mm (177 in) in length.

32. The reactor of claim 1, wherein said interstage heat exchanger is capable of maintaining a process gas leaving the interstage heat exchanger at a temperature ranging from 240 °C to 280 °C.

33. A method of making acrylic acid, comprising oxidizing propylene in the reactor of claim 1.

34. A single shell open interstage stage reactor, comprising, in process-flow order:

a) a shell-and-tube first reaction stage comprising a plurality of reaction tubes containing a first catalyst;

b) an integrated interstage heat exchanger comprising a plurality of tubes coaxially continuous with the plurality of reaction tubes of the first reaction stage;

c) an open interstage region comprising a supplemental oxidant mixing assembly; and

d) a shell-and-tube second reaction stage comprising a plurality of reaction tubes containing a second catalyst.

35. The reactor of claim 34, wherein said integrated interstage heat exchanger comprises a shellside coolant controlled independently of a shellside coolant of said first reaction stage.

36. The reactor of claim 34, wherein said supplemental oxidant mixing assembly comprises a supplemental oxidant supply line, optionally an oxidant heat exchanger, and a venturi mixer.

37. The reactor of claim 36, wherein said venturi mixer comprises:

a) an inlet contracting section;

b) an intermediate throat section comprising at least one blending element; and

c) an outlet expansion section.

38. The reactor of claim 37, wherein the at least one blending element is selected from the group consisting of nozzles, injectors, gas-gas mixing elements, distributors, aspirators, coanda-effect mixing elements, spargers, static mixing elements, eductors, lances, and combinations thereof.

39. The reactor of claim 37, wherein said intermediate throat section does not comprise high surface area inert material.

40. The reactor of claim 37, wherein said outlet expansion section does not comprise high surface area inert material.

41. The reactor of claim 37, wherein said inlet contracting section comprises particulate inert material having a bulk void fraction of less than 50%.

42. The reactor of claim 34, wherein said integrated interstage heat exchanger is capable of maintaining a process gas leaving the integrated interstage heat exchanger at a temperature ranging from 240 °C to 280 °C.

43. The reactor of claim 34, wherein said open interstage region is at least partially filled with at least one high surface area inert material having a surface area to bulk volume ratio of at least 78.7 m^2/cubic m (24 ft^2/ cubic foot).

44. The reactor of claim 34, wherein said open interstage region is at least partially filled with at least one high surface area inert material in an amount sufficient to provide at least 2790 m^2 (30,000 ft^2) of total surface area.

45. The reactor of claim 34, wherein said open interstage region is uncooled.

46. The reactor of claim 34, wherein said integrated interstage heat exchanger further comprises turbulence inducing inserts within the plurality of tubes.

47. The reactor of claim 34, wherein said inserts have a void fraction of at least 85%.

48. The reactor of claim 34, wherein the reaction tubes of the second reaction stage have a greater cross-sectional area than the reaction tubes of the first reaction stage.

49. The reactor of claim 48, wherein the reaction tubes of the second reaction stage have a cross-sectional area at least 30% greater than the cross-sectional area of the reaction tubes of the first reaction stage.

50. The reactor of claim 49, wherein the reaction tubes of the second reaction stage have a cross-sectional area at least 50% greater than the cross-sectional area of the reaction tubes of the first reaction stage.

51. The reactor of claim 34, further comprising an inlet reactor head and an outlet reactor head.

52. The reactor of claim 51, wherein at least one of said inlet reactor head and said outlet reactor head is removable.

53. The reactor of claim 34, wherein said reactor is configured for upflow operation.

54. A method of making acrylic acid, comprising oxidizing propylene in the reactor of claim 34.

55. A single shell open interstage reactor comprising:

a) a first shell-and-tube reaction stage comprising a plurality of reaction tubes;

b) an interstage heat exchanger;

c) an open interstage region; and

d) a second shell-and-tube reaction stage comprising a plurality of reaction tubes;

wherein the reaction tubes of the second reaction stage have a diameter greater than a diameter of the reaction tubes of said first reaction stage.

56. The reactor of claim 55, wherein said tubes of the second reaction stage have a diameter greater than 22.3 mm (0.878 in).

~~57. The reactor of claim 56, wherein said tubes of the second reaction stage have a diameter greater than 25.4 mm (1.0 in).~~

~~58. The reactor of claim 55, comprising a greater number of reaction tubes in the first reaction stage than in the second reaction stage.~~

~~59. The reactor of claim 55, wherein the reaction tubes of said first reaction stage have a diameter less than 25.4 mm (1.0 in) and the reaction tubes of said second reaction stage have a diameter greater than or equal to 25.4 mm (1.0 in).~~

~~60. The reactor of claim 55, wherein the reaction tubes of said second reaction stage have a cross-sectional area at least 25% greater than a cross-sectional area of the reaction tubes of said first reaction stage.~~

~~61. The reactor of claim 60, wherein the reaction tubes of said second reaction stage have a cross-sectional area at least 50% greater than a cross-sectional area of the reaction tubes of said first reaction stage.~~

~~62. The reactor of claim 55, further comprising a catalyst retaining device located between said first reaction stage and said interstage heat exchanger.~~

~~63. The reactor of claim 55, wherein said first reaction stage comprises a catalyst retaining device located at an end of said first reaction stage opposite from said interstage heat exchanger.~~

~~64. The reactor of claim 55, wherein said open interstage region comprises a supplemental gas supply line.~~

~~65. The reactor of claim 65, wherein said open interstage region further comprises a supplemental gas mixing assembly.~~

~~66. The reactor of claim 65, wherein said supplemental gas mixing assembly comprises a venturi mixer.~~

~~67. The reactor of claim 64, wherein said supplemental gas supply line comprises an gas heat exchanger.~~

68. The reactor of claim 55, wherein the reaction tubes of the first shell-and-tube reaction stage comprise a first catalyst for oxidizing propylene to produce acrolein.

69. The reactor of claim 55, wherein the reaction tubes of the second shell-and-tube reaction stage comprise a second catalyst for oxidizing acrolein to produce acrylic acid.

70. The reactor of claim 55, wherein said interstage heat exchanger is capable of maintaining a process gas leaving the integrated interstage heat exchanger at a temperature ranging from 240 °C to 280 °C.

71. The reactor of claim 55, wherein said open interstage region is at least partially filled with at least one high surface area inert material having a surface area to bulk volume ratio of at least 78.7 m^2/cubic m (24 ft^2/ cubic foot).

72. The reactor of claim 55, wherein said open interstage region is at least partially filled with at least one high surface area inert material in an amount sufficient to provide at least 2790 m^2 (30,000 ft^2) of total surface area.

73. A method of making acrylic acid, comprising oxidizing propylene in the reactor of claim 55.

74. A single shell open interstage reactor for producing acrylic acid from propylene comprising, in process-flow order:

a) a first shell-and-tube reaction stage comprising a plurality of reaction tubes, wherein the reaction tubes of the first reaction stage comprise a first catalyst for oxidizing propylene to produce acrolein;

b) an interstage heat exchanger;

c) an open interstage region; and

d) a second shell-and tube reaction stage comprising a plurality of reaction tubes, wherein the reaction tubes of the second reaction stage comprise a second catalyst for oxidizing acrolein to produce acrylic acid; and

wherein the reaction tubes of the second reaction stage have a diameter greater than 22.3 mm (0.878 in).

75. The reactor of claim 74, wherein said open interstage region comprises a supplemental oxidant supply line.

76. The reactor of claim 75, wherein said open interstage region further comprises a supplemental oxidant mixing assembly.

77. The reactor of claim 76, wherein said supplemental oxidant mixing assembly comprises a supplemental oxidant supply line, optionally an oxidant heat exchanger, and a venturi mixer.

78. The reactor of claim 77, wherein said venturi mixer comprises:

a) an inlet contracting section;

b) an intermediate throat section comprising at least one blending element; and

c) an outlet expansion section.

79. The reactor of claim 78, wherein the at least one blending element is selected from the group consisting of nozzles, injectors, gas-gas mixing elements, distributors, aspirators, coanda-effect mixing elements, spargers, static mixing elements, eductors, lances, and combinations thereof.

80. The reactor of claim 78, wherein said inlet contracting section comprises particulate inert material having a bulk void fraction of less than 50%.

81. The reactor of claim 74, wherein said open interstage region is at least partially filled with at least one inert material.

82. The reactor of claim 81, wherein said at least one inert material has a surface area to bulk volume ratio of at least 78.7 m^2/cubic m (24 ft^2/ft^3).

83. The reactor of claim 81, wherein said at least one inert material is present in an amount sufficient to provide at least 2790 m^2 (30,000 ft^2) of total surface area.

84. The reactor of claim 74, wherein said first catalyst comprises at least one compound chosen from oxides of molybdenum, bismuth, and iron.

~~85. The reactor of claim 74, wherein said second catalyst comprises at least one compound chosen from oxides of molybdenum and vanadium.~~

~~86. The reactor of claim 74, wherein said interstage heat exchanger comprises inserts having a void fraction of at least 85%.~~

~~87. The reactor of claim 74, wherein the mass of said second catalyst is about 0.95 to about 1.65 times the mass of said first catalyst.~~

~~88. The reactor of claim 87, wherein the mass of said second catalyst is about 1.25 to about 1.6 times the mass of said first catalyst.~~

~~89. The reactor of claim 74, wherein said interstage heat exchanger is capable of maintaining a process gas leaving the interstage heat exchanger at a temperature ranging from 240 °C to 280 °C.~~

~~90. A method of making acrylic acid, comprising oxidizing propylene in the reactor of claim 74.~~

CLAIMS

~~91~~1. A process of making acrylic acid comprising the following steps in process flow order:

a) providing a mixed feed gas comprising propylene to a first reaction stage ~~located at a lower end~~ of a single shell open interstage ~~reactor~~ shell and tube reactor comprising a plurality of reaction tubes, wherein the first reaction stage comprises a mixed metal oxide catalyst for oxidizing propylene to acrolein;

b) oxidizing the propylene in the first reaction stage to produce a process gas comprising acrolein;

c) cooling the process gas in an interstage heat exchanger disposed between the first reaction stage and a second reaction stage;

d) passing the cooled process gas ~~upward~~ through an open interstage region;

e) passing the process gas ~~upward~~ to a second shell and tube reaction stage comprising a plurality of reaction tubes, wherein the second reaction stage comprises a mixed metal oxide catalyst for oxidizing acrolein to acrylic acid; and

f) oxidizing the acrolein in the second reaction stage to produce a product gas comprising acrylic acid.

~~92~~2. The process of claim ~~91~~1, wherein the mixed feed gas comprises at least 7.5 mol% propylene.

~~93~~3. The process of claim ~~91~~1, wherein the mixed feed gas further comprises oxygen at an oxygen-to-propylene molar ratio of between 1.6 and 2.0.

~~94~~4. The process of claim ~~91~~1, wherein the mixed feed gas further comprises water vapor at a water vapor-to-propylene molar ratio of about 1.2 or less.

~~95~~5. The process of claim ~~91~~1, wherein the mixed feed gas is provided to the first reaction stage at a temperature greater than the dewpoint temperature of the mixed feed gas.

~~96~~6. The process of claim ~~91~~1, wherein cooling the process gas comprises cooling the process gas to a temperature not greater than 280 °C.

~~97~~7. The process of claim ~~96~~6, wherein cooling the gas comprises cooling the process gas to a temperature ranging from 240 °C to 280 °C.

~~98~~8. The process of claim ~~91~~1, further comprising providing supplemental oxidant to the process gas in the open interstage region.

~~99~~9. The process of claim ~~98~~8, further comprising mixing the process gas and supplemental oxidant in the open interstage region.

~~100~~10. The process of claim ~~99~~9, wherein mixing the process gas and supplemental oxidant in the open interstage region comprises mixing in a mixing device.

~~101~~11. The process of claim ~~91~~1, wherein the process gas is present in the interstage heat exchanger for a residence time of not more than 1.5 seconds.

~~102~~12. The process of claim ~~91~~1, wherein the process gas is present in the interstage heat exchanger and the open interstage for a residence time of not more than 3 seconds.

~~103~~13. The process of claim ~~91~~1, wherein passing the cooled process gas through an open interstage comprises removing foulants from the process gas by passing the process gas through an inert material having a total surface area of at least 930 m^2 ~~(10,000 ft^2)~~.

~~104~~14. The process of claim ~~103~~13, wherein the inert material has a total surface area of at least 2790 m^2 ~~(30,000 ft^2)~~.

~~105~~15. The process of claim ~~91~~1, wherein the mixed metal oxide catalyst in the first reaction stage comprises at least one compound selected from the group consisting of oxides of molybdenum, bismuth, and iron.

~~106~~16. The process of claim ~~91~~1, wherein the mixed metal oxide catalyst in the second reaction stage comprises at least one compound selected from the group consisting of oxides of molybdenum and vanadium.

~~107~~17. The process of claim ~~91~~1, further comprising circulating a coolant through the first reaction stage, the interstage heat exchanger, and the second reaction stage.

~~108~~18. The process of claim ~~107~~17, wherein the coolant is circulated independently in at least one of the first reaction stage, the interstage heat exchanger, and the second reaction stage.

~~109~~19. The process of claim ~~91~~17, wherein the coolant is circulated in a co-current configuration.

~~110~~20. The process of claim ~~91~~1, wherein the interstage heat exchanger comprises inserts and cooling the process gas does not condense the process gas on the surface of the inserts.

~~111~~21. The process of claim ~~91~~1, wherein the mass of catalyst in the second reaction stage is about 0.95 to about 1.65 times the mass of catalyst in the first reaction stage.

~~112~~22. The process of claim 21~~11~~, wherein the mass of catalyst in the second reaction stage is about 1.25 to about 1.6 times the mass of catalyst in the first reaction stage.

~~113~~23. The process of claim ~~91~~1, further comprising:

i) cooling the product gas to form a cooled product gas;

ii) transferring the cooled product gas to a solvent-free acrylic acid collection and purification system comprising a dehydration column and a finishing column;

iii) removing an overhead vapor stream comprising non-condensable gases and water vapor from the dehydration column;

iv) removing a side draw acrylic acid stream comprising at least 98 wt% acrylic acid from the finishing column; and

(v) removing a bottoms recirculation stream comprising heavy ends from the finishing column.

~~11~~24. The process of claim ~~11~~23, further comprising processing the side draw acrylic acid stream in a melt crystallization process.

~~11~~525. The process of claim ~~11~~323, further comprising transferring at least a portion of the bottoms recirculation stream comprising heavy ends to an ester process comprising a dimer cracker.

~~11~~626. The process of claim ~~11~~323, further comprising:

vi) dividing the overhead vapor stream comprising non-condensable gases and water vapor into a recycle gas stream and a purge stream;

vii) returning the recycle gas stream to the single shell open interstage reactor; and

viii) processing the purge stream in one or more of a catalytic combustion unit, a thermal oxidizer, and a waste heat recovery system.

~~11~~727. The process of claim ~~11~~526, wherein the mass flow rate of the recycle gas stream is between 5% and 50% of the mass flow rate of the overhead vapor stream comprising non-condensable gases and water vapor.

28. The process of claim 1 wherein the reaction tubes of the second reaction stage have a diameter greater than 22.3 mm.