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(54) Title: FALLING BED REACTOR

(57) Abstract: Methods and apparatuses are provided for pyrolysis using a falling bed reactor. The falling bed reactor may result in effective mixing between a heat carrier and biomass, and may reduce or eliminate inert gas requirements.

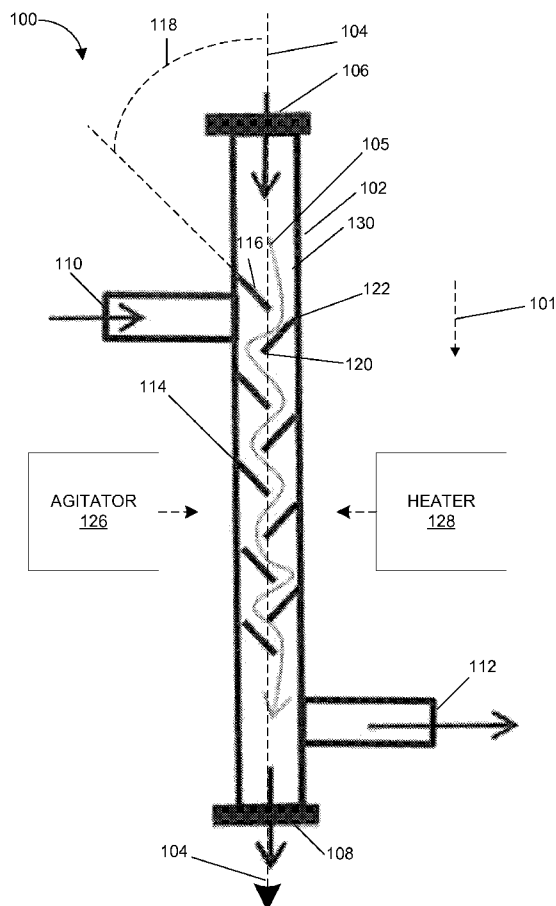


FIG. 1



AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

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## **FALLING BED REACTOR**

### CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority from U.S. Provisional Patent Application No. 61/826,989, filed on May 23, 2013, which is incorporated by reference herein in its entirety.

### **BACKGROUND**

[0002] Biomass pyrolysis is conventionally conducted using bubbling fluid beds, circulating fluid bed transport reactors, rotating cone reactors, ablative reactors or auger reactors. Fluidized bed designs such as bubbling fluid bed reactors and circulating fluid bed reactors may provide high heat transfer rates to the substrate, e.g., biomass, and these high heat transfer rates may result in high yield of bio-oil. A disadvantage of fluidized bed systems is that a significant flow rate of inert gas may be needed, which may lead to undesirable parasitic losses. Other designs, such as rotating cone reactors and auger reactors may not require significant inert gas flow, but mixing between the heat carrier and biomass may not be as effective as with fluidized beds, which may lead to lower reaction yields, e.g., of bio-oil from bio-mass pyrolysis. The present application appreciates that biomass pyrolysis may be a challenging endeavor.

### **SUMMARY**

[0003] In one embodiment, a falling bed reactor is provided. The falling bed reactor may include a reactor conduit defining a flow axis. The falling bed reactor may include an inlet operatively coupled to receive a heat carrier particulate into the reactor conduit. The falling bed reactor may also include an outlet operatively coupled to direct the heat carrier particulate out of the reactor conduit. The falling bed reactor may also include one or more baffles mounted in the reactor conduit, e.g., a plurality of baffles.

**[0004]** In another embodiment, a falling bed reactor is provided. The falling bed reactor may include a reactor conduit defining a flow axis. The falling bed reactor may include an inlet operatively coupled to receive a heat carrier particulate into the reactor conduit. The falling bed reactor may also include an outlet operatively coupled to direct the heat carrier particulate out of the reactor conduit. The falling bed reactor may further include a pyrolysis substrate inlet operatively coupled to receive a pyrolysis substrate into the reactor conduit. The falling bed reactor may include a pyrolysis product outlet operatively coupled to direct a pyrolysis product out of the reactor conduit. The falling bed reactor may also include one or more baffles mounted in the reactor conduit, e.g., a plurality of baffles. Each baffle in the one or more baffles may include a baffle surface. At least a portion of each baffle surface may be at an oblique angle with respect to the flow axis.

**[0005]** In one embodiment, a pyrolysis system is provided. The pyrolysis system may include a falling bed reactor and a cross-flow classifier. The falling bed reactor may include a reactor conduit defining a flow axis. The falling bed reactor may include an inlet operatively coupled to receive a heat carrier particulate into the reactor conduit. The falling bed reactor may also include an outlet operatively coupled to direct the heat carrier particulate out of the reactor conduit. The falling bed reactor may further include a pyrolysis substrate inlet operatively coupled to receive a pyrolysis substrate into the reactor conduit. The falling bed reactor may include a pyrolysis product outlet operatively coupled to direct a pyrolysis product out of the reactor conduit. The falling bed reactor may also include one or more baffles mounted in the reactor conduit. Each baffle in the one or more baffles may include a baffle surface. At least a portion of each baffle surface may be at an oblique angle with respect to the flow axis.

**[0006]** The cross-flow classifier may include a separator conduit. The cross-flow classifier may also include a flow input and a flow output in fluidic communication with the

separator conduit. The separator conduit may extend between the flow input and the flow output to define a flow axis along at least a portion of the separator conduit. The flow input may be located upstream of the flow output with respect to the flow axis. The cross-flow classifier may include a cross-flow input and a cross-flow output in fluidic communication with the separator conduit between the flow input and the flow output. The cross-flow input may be located upstream of the cross-flow output with respect to the flow axis. The cross-flow input may define a cross-flow axis intersecting the flow axis at a cross-flow angle between about 70° and about 180° with respect to the flow axis. Further with respect to the pyrolysis system, the outlet of the falling bed reactor may be operatively coupled to the flow input of the cross-flow classifier. Also, the flow output of the cross-flow classifier may be operatively coupled to the inlet of the falling bed reactor.

[0007] In one embodiment, a pyrolysis method is provided. The pyrolysis method may include feeding a heat carrier to a gravity-fed baffled conduit. The pyrolysis method may include feeding a pyrolysis substrate to the gravity-fed baffled conduit such that the heat carrier and the pyrolysis substrate mix to form a pyrolysis mixture. The pyrolysis method may include heating the heat carrier and/or the gravity-fed baffled conduit to pyrolyze the pyrolysis substrate in the pyrolysis mixture to form a pyrolysis product mixture. The “gravity-fed baffled conduit” may include, for example, the falling bed reactor.

#### **BRIEF DESCRIPTION OF THE DRAWINGS**

[0008] The accompanying figures, which are incorporated in and constitute a part of the specification, illustrate example methods and apparatuses, and are used merely to illustrate example embodiments.

[0009] **FIG. 1** depicts an example falling bed reactor;

[0010] FIG. 2 depicts an example pyrolysis system that includes an example falling bed reactor and an example cross-flow particle classifier;

[0011] FIG. 3 is a block diagram of an example cross-flow particle classifier; and

[0012] FIG. 4 is a flow diagram of an example method for pyrolysis.

### DETAILED DESCRIPTION

[0013] FIG. 1 depicts an example falling bed reactor **100**. Falling bed reactor **100** may include a reactor conduit **102** defining a flow axis **104**. Flow axis **104** may have a downstream end, indicated by the arrowhead, and an upstream end, indicated by the shaft end of the arrow. Falling bed reactor **100** may include an inlet **106** operatively coupled to receive a heat carrier particulate into reactor conduit **102**. Falling bed reactor **100** may also include an outlet **108** operatively coupled to direct the heat carrier particulate out of reactor conduit **102**. Falling bed reactor **100** may further include a pyrolysis substrate inlet **110** operatively coupled to receive a pyrolysis substrate into reactor conduit **102**. Falling bed reactor **100** may include a pyrolysis product outlet **112** operatively coupled to direct a pyrolysis product out of reactor conduit **102**. Falling bed reactor **100** may also include one or more baffles **114**, e.g., a plurality of baffles, mounted in reactor conduit **102**. Each baffle in one or more baffles **114** may include a baffle surface **116**. At least a portion of each baffle surface **116** may be at an oblique angle **118** with respect to flow axis **104**.

[0014] As used herein, the “heat carrier” may be a particulate including one or more of: a metal, a glass, a ceramic, a mineral, or a polymeric composite. For example, the heat carrier may be sand. The heat carrier may include a particulate catalyst. For example, the heat carrier may include a fluid catalytic cracking (FCC) catalyst. The heat carrier may include a spent particulate catalyst. For example, the heat carrier may include a spent FCC catalyst. The heat carrier may be in the form of metal shot, for example, steel shot. In various

embodiments, the heat carrier, when employed with the cross flow particle classifier, is of a density effective to provide separation between the heat carrier and the char to be separated in the cross flow particle classifier.

[0015] As used herein, an “oblique angle” is any angle that is not an integer multiple of a right angle. For example, an oblique angle excludes 0°, 90°, and 180°, but includes angles between 0° and 90°, and angles between 90° and 180°.

[0016] In various embodiments, falling bed reactor **100** may be configured to be mounted such that at least a portion of flow axis **104** is parallel or oblique to a vertically downward direction. Falling bed reactor **100** may be configured to be mounted such that at least a portion of each baffle surface **116** is at an oblique angle **118** with respect to the vertically downward direction. Falling bed reactor **100** may be mounted to orient flow axis **104** in a substantially vertically downward direction. In this manner, falling bed reactor **100** may be gravity-fed or gravity operated, at least in part. For example, the pyrolysis substrate may enter falling bed reactor **100** at pyrolysis substrate inlet **110**, and the heat carrier particulate may enter falling bed reactor **100** at inlet **106**. The pyrolysis substrate and the heat carrier particulate may fall through falling bed reactor **100**, and may be intermittently diverted from flow axis **104** by one or more baffles **114**, for example, as indicated by a path **105**.

[0017] In some embodiments, a cross section of reactor conduit **102** may include a shape that may be one of: polygonal, rounded polygonal, circular, elliptical, or a combination or composite thereof. A cross section of reactor conduit **102** may include a shape that may be one of: rectangular, rounded rectangular, circular, elliptical, or a combination or composite thereof. For example, reactor conduit **102** may be square in cross section.

[0018] In several embodiments, one or both of inlet **106** and outlet **108** may be substantially parallel with one or both of reactor conduit **102** and flow axis **104**. Inlet **106**

may be operatively coupled to reactor conduit **102** upstream of outlet **108** with respect to flow axis **104**.

[0019] In some embodiments, falling bed reactor **100** may include a pyrolysis substrate inlet **110** operatively coupled to receive a pyrolysis substrate into reactor conduit **102**. Falling bed reactor **100** may include a pyrolysis product outlet **112** operatively coupled to direct a pyrolysis product out of reactor conduit **102**.

[0020] Pyrolysis substrate inlet **110** may be operatively coupled to reactor conduit **102** upstream of pyrolysis product outlet **112** with respect to flow axis **104**. Pyrolysis substrate inlet **110** may be operatively coupled to reactor conduit **102** upstream of pyrolysis product outlet **112** with respect to flow axis **104**. Pyrolysis substrate inlet **110** may be operatively coupled to reactor conduit **102** at a same level or downstream of pyrolysis product outlet **112** with respect to flow axis **104**. Pyrolysis substrate inlet **110** may be coincident with inlet **106**. Pyrolysis product outlet **112** may be coincident with inlet **106** or outlet **108**.

[0021] In various embodiments, the one or more baffles **114** may extend from an inside wall **130** of the reactor conduit **102** into the reactor conduit **102**. For example, the one or more baffles **114** may extend from the inside wall **130** to define a cantilevered geometry in the reactor conduit **102**. The one or more baffles **114** may extend across at least a portion of the reactor conduit **102** between a first portion of the inside wall **130** and a second portion of the inside wall **130**. Each of the one or more baffles **114** may include a form of one or more of a rod, a plate, a screen, or a protrusion. Each of the one or more baffles **114** may include a form of a rod. The rod may include a cross-sectional geometry that is at least in part polygonal, rounded polygonal, circular, elliptical, or a combination or composite thereof.

[0022] In some embodiments, each of the one or more baffles **114** may include a baffle surface **116**. The baffle surface **116** may be positioned to intersect at least a portion of the reactor conduit **102** with respect to the flow axis **104**. At least a portion of the baffle surface



**116** may include a geometry that is one or more of flat or convex. At least a portion of the baffle surface **116** may be horizontal with respect to the flow axis **104**. At least a portion of the baffle surface **116** may be at an oblique angle **118** with respect to the flow axis **104**.

[0023] In various embodiments, one or more baffles **114** may be mounted to place at least the portion of each baffle surface **116** at oblique angle **118** with respect to flow axis **104** such that one or more baffles **114** may form a staggered or alternating pattern in reactor conduit **102**. Each baffle in one or more baffles **114** may be mounted to an inside wall **130** of reactor conduit **102** to define a free edge **120** of each baffle surface **116** and a mounted edge **122** of each baffle surface. In some embodiments, one or more baffles **114** may be configured as an alternating sequence of funnels and cones, the funnels aligned with the flow axis **104** and the cones aligned antiparallel to the flow axis **104**, each of the funnels and cones may include a free edge **120** at a downstream extremity of each of the funnels and cones. In some embodiments, the staggered or alternating pattern of one or more baffles **114** intersecting flow axis **104** to provide a tortuous flow path through one or more baffles **114**. Each baffle surface **116** in one or more baffles **114** may be substantially at oblique angle **118** with respect to flow axis **104**. For example, oblique angle **118** may be between about 30° and about 60° with respect to flow axis **104** such that for each baffle surface **116**, a free edge **120** of baffle surface **116** may be further downstream along flow axis **104** compared to a mounted edge **122** of baffle surface **116**.

[0024] In several embodiments, falling bed reactor **100** may include an agitator mechanism **126** configured to agitate at least a portion of one or more baffles **114** effective to dislodge a particulate on at least a portion of one or more baffles **114**. Falling bed reactor **100** may include a heater **128**. Heater **128** may be configured cause pyrolysis of a substrate in falling bed reactor **100** by heating one or both of falling bed reactor **100** and a heat carrier to be fed into falling bed reactor **100**.

[0025] FIG. 2 depicts an example pyrolysis system 200. Pyrolysis system 200 may include falling bed reactor 100 and a cross-flow classifier 3100. Falling bed reactor 100 may include a reactor conduit 102 defining a flow axis 104. Flow axis 104 may have a downstream end, indicated by the arrowhead, and an upstream end, indicated by the shaft end of the arrow. Falling bed reactor 100 may include an inlet 106 operatively coupled to receive a heat carrier particulate into reactor conduit 102. Falling bed reactor 100 may also include an outlet 108 operatively coupled to direct the heat carrier particulate out of reactor conduit 102. Falling bed reactor 100 may further include a pyrolysis substrate inlet 110 operatively coupled to receive a pyrolysis substrate into reactor conduit 102. Falling bed reactor 100 may include a pyrolysis product outlet 112 operatively coupled to direct a pyrolysis product out of reactor conduit 102. Falling bed reactor 100 may also include one or more baffles 114 mounted in reactor conduit 102. Each baffle in one or more baffles 114 may include a baffle surface 116. At least a portion of each baffle surface 116 may be at an oblique angle 118 with respect to flow axis 104.

[0026] Cross-flow classifier 3100 may include a separator conduit 3102. Cross-flow classifier 3100 may also include a flow input 3104 and a flow output 3106 in fluidic communication with separator conduit 3102. Separator conduit 3102 may extend between flow input 3104 and flow output 3106 to define a flow axis 3108 along at least a portion of separator conduit 3102. Flow input 3104 may be located upstream of flow output 3106 with respect to flow axis 3108. Cross-flow classifier 3100 may include a cross-flow input 3114 and a cross-flow output 3116 in fluidic communication with separator conduit 3102 between flow input 3104 and flow output 3106. Cross-flow input 3114 may be located upstream of cross-flow output 3116 with respect to flow axis 3108. Cross-flow input 3114 may define a cross-flow axis 3118 intersecting flow axis 3108 at a cross-flow angle 3120 between about 70° and about 180° with respect to flow axis 3108. Further with respect to pyrolysis system

**200**, outlet **108** of falling bed reactor **100** may be operatively coupled to flow input **3104** of cross-flow classifier **3100**. Also, flow output **3106** of cross-flow classifier **3100** may be operatively coupled to inlet **106** of falling bed reactor **100**.

[0027] In various embodiments, outlet **108** of falling bed reactor **100** may be operatively coupled to flow input **3104** of cross-flow classifier **3100** via an auger or conveyor **230**. Flow output **3106** of cross-flow classifier **3100** may be operatively coupled to inlet **106** of falling bed reactor **100** via an auger or conveyor **232**.

[0028] In some embodiments, pyrolysis system **200** may include a fine particulate separator **202**. An input **204** of fine particulate separator **202** may be operatively coupled to pyrolysis product outlet **112** of falling bed reactor **100**. Fine particulate separator **202** may include a particulate outlet **206** and a gas or vapor outlet **208**. For example, fine particulate separator **202** may include one or more of: a settling chamber, a baffle chamber, a cyclonic particle separator, an electrostatic precipitator, a filter, or a scrubber

[0029] In several embodiments, pyrolysis system **200** may include a coarse particulate separator **212**. An input **214** of coarse particulate separator **212** may be operatively coupled to cross-flow output **3116** of cross-flow classifier **3100**. Coarse particulate separator **212** may include a particulate outlet **216** and a gas outlet **218**. For example, coarse particulate separator **212** may include one or more of: a settling chamber, a baffle chamber, a cyclonic particle separator, an electrostatic precipitator, a filter, or a scrubber

[0030] In various embodiments, pyrolysis system **200** may include a gas recycle conduit **220**. Gas recycle conduit **220** may be operatively coupled to receive recycled gas from gas outlet **218**. Gas recycle conduit **220** may be operatively coupled to direct the recycled gas to cross-flow input **3114** of cross-flow classifier **3100**. In some embodiments, gas recycle conduit **220** may include a fan **222**. Fan **222** may be configured to draw the recycled gas from gas outlet **218** via gas recycle conduit **220**. Fan **222** may be configured to flow the

recycled gas to cross-flow input **3114** of cross-flow classifier **3100** via gas recycle conduit **220**.

[0031] In further embodiments, falling bed reactor **100** in pyrolysis system **200** may include any aspect of falling bed reactor **100** described herein.

[0032] FIGS. 3A and 3B depict aspects of cross-flow classifier **3100** that may be used in example pyrolysis system **200**. For example, in various embodiments, one or both of flow input **3114** and flow output **3116** may be substantially aligned with flow axis **3108** of separator conduit **3102**. In some embodiments, cross-flow input **3114** may be operatively coupled to separator conduit **3102** substantially opposite to cross-flow output **3116** with respect to flow axis **3108**.

[0033] In some embodiments, cross-flow classifier **3100** may be mounted such that flow axis **3108** points downward at a flow angle **3110**. For example, flow angle **3110** may be less than 90° from vertically downward. In some embodiments, flow angle **3110** may be less than 60° from vertically downward.

[0034] As used herein, “downward” means any direction represented by a vector having a non-zero component parallel with respect to a local gravitational acceleration direction. As used herein, “upward” means any direction represented by a vector having a non-zero component antiparallel with respect to the local gravitational acceleration direction. As used herein, “vertical” means parallel or antiparallel with respect to the local gravitational acceleration direction. “Vertically downward” means parallel with respect to the local gravitational acceleration direction, indicated in FIG. 1 by arrow **3101**. “Vertically upward” means antiparallel with respect to the local gravitational acceleration direction. As used herein, “horizontal” means perpendicular to the local gravitational acceleration direction.

[0035] In several embodiments, separator conduit **3102** may include a first flow diameter **3122** between flow input **3104** and cross-flow input **3114**. Separator conduit **3102** may

include a second flow diameter **3124** downstream of cross-flow input **3114**. First flow diameter **3122** may be greater than second flow diameter **3124**. Separator conduit **3102** may include a transition **3126** between first flow diameter **3122** and second flow diameter **3124**. Transition **3126** may be substantially aligned with cross-flow angle **3120**. For example, transition **3126** may be substantially perpendicular with respect to flow axis **3108**.

[0036] In various embodiments, flow input **3104** may be configured to accept a plurality of particulates. At least a first particulate in the plurality of particulates may be characterized by a first average density. At least a second particulate in the plurality of particulates may be characterized by a second average density greater than the first average density. Flow output **3106** may be configured to convey at least a portion of the first particulate characterized by the first density out of separator conduit **3102**. Cross-flow output **3116** may be configured to convey at least a portion of the second particulate characterized by the second density greater than the first density out of separator conduit **3102**.

[0037] As used herein, a “particulate” refers to a plurality, collection, or distribution of individual particles. The individual particles in the particulate may have in common one or more characteristics, such as size, density, material composition, heat capacity, particle morphology, and the like. The characteristics of the particles in the particulate may be the same among the particles, or may be characterized by a distribution. For example, particles in a particulate may all be made of the same composition, e.g., a ceramic, a metal, or the like. In another example, particles in a particulate may be characterized by a distribution of particle sizes, for example, a Gaussian distribution.

[0038] In some embodiments, cross-flow input **3114** may define a first convergent nozzle **3132**. First convergent nozzle **3132** may include a first nozzle throat **3134**. A cross section of first nozzle throat **3134** may include at least two dissimilar axes. For example, first nozzle throat **3134** may include an elliptical cross section, a circular cross section, a rectangular

cross section, a rounded corner rectangular cross section, a polygonal cross section, a composite or combination thereof, or the like.

[0039] In several embodiments, the first nozzle throat **3134** may be operatively coupled to a nozzle exit zone. At least a portion of the nozzle exit zone may include a transition **3126** between a first flow diameter **3122** of flow conduit **3108** and first nozzle throat **3134**. In some embodiments, at least a portion of the nozzle exit zone may include a second flow diameter **3124** of separator conduit **3108**. Transition **3126** may be located at an upstream side of first nozzle throat **3134**. Second flow diameter **3124** may be located at a downstream side of first nozzle throat **3134**. First nozzle throat **3134** may be located at second flow diameter **3124** of separator conduit **3108**.

[0040] In various embodiments, convergent nozzle **3132** of cross-flow input **3114** may include a second nozzle throat **3138**. First nozzle throat **3134** may be located at cross-flow input **3114** between second nozzle throat **3138** and separator conduit **3108**. Cross-flow output **3116** may define a second convergent nozzle **3142**.

[0041] In some embodiments, second convergent nozzle **3142** may include a third nozzle throat **3144**. A cross section of third nozzle throat **3144** may include at least two dissimilar axes. For example, third nozzle throat **3144** may include an elliptical cross section, a circular cross section, a rectangular cross section, a rounded corner rectangular cross section, a polygonal cross section, a composite or combination thereof, or the like. Third nozzle throat **3144** may be operatively coupled to a nozzle entrance zone **3146**. At least a portion of nozzle entrance zone **3146** may include a transition **3148** between a second flow diameter **3124** of flow conduit **3108** and third nozzle throat **3144**. In some embodiments, at least a portion of nozzle entrance zone **3146** may include an entrance vane **3150**. Entrance vane **3150** may extend into separator conduit **3102**, for example, with respect to second flow diameter **3124**.

At least a portion of entrance vane **3150** may extend into separator conduit **3102** at least partly in an upstream direction with respect to flow axis **3108**.

[0042] In several embodiments, third nozzle throat **3144** may be operatively coupled through a nozzle collector zone to an exit conduit **3154**. One or both of the nozzle collector zone and conduit **3154** may include an elliptical cross section. For example, one or both of the nozzle collector zone and exit conduit **3154** may include a circular cross section. Third nozzle throat **3144** may be operatively coupled to an exit conduit **3154**. Exit conduit **3154** may define an exit conduit axis **3156**. Exit conduit axis **3156** may intersect flow axis **3108** at an exit angle **3158**. Exit angle **3158** may be greater than  $0^\circ$  and less than  $180^\circ$ . For example, exit angle **3158** may be between about  $90^\circ$  and less than  $180^\circ$ . In some embodiments, exit conduit axis **3156** may be within about  $30^\circ$  of vertical.

[0043] FIG. 4 is a flow diagram describing an example pyrolysis method **400**. Pyrolysis method **400** may include feeding a heat carrier to a gravity-fed baffled conduit (step **402**). Pyrolysis method **400** may include feeding a pyrolysis substrate to the gravity-fed baffled conduit such that the heat carrier and the pyrolysis substrate mix to form a pyrolysis mixture (step **404**). Pyrolysis method **400** may include heating the heat carrier and/or the gravity-fed baffled conduit to pyrolyze the pyrolysis substrate in the pyrolysis mixture to form a pyrolysis product mixture (step **406**). The gravity-fed baffled conduit may include, for example, the falling bed reactor **100** described herein.

[0044] In various embodiments of pyrolysis method **400**, the pyrolysis product mixture may include a gas or vapor pyrolysis product and a fine char pyrolysis product. The method may include directing the gas or vapor pyrolysis product and the fine char pyrolysis product out of the gravity-fed baffled conduit. The pyrolysis product mixture may include the heat carrier and a coarse char pyrolysis product. The method may further include directing the heat carrier and the coarse char pyrolysis product out of the gravity-fed baffled conduit. In

some examples, the method may include directing the gas or vapor pyrolysis product and the fine char pyrolysis product out of the gravity-fed baffled conduit at the same level as the heat carrier and the coarse char pyrolysis product. The method may include directing the gas or vapor pyrolysis product and the fine char pyrolysis product out of the gravity-fed baffled conduit upstream compared to the heat carrier and the coarse char pyrolysis product. The method may include directing the gas or vapor pyrolysis product and the fine char pyrolysis product out of the gravity-fed baffled conduit downstream compared to the heat carrier and the coarse char pyrolysis product

**[0045]** In some embodiments, the pyrolysis product mixture may include the heat carrier and a coarse char pyrolysis product. The method may include directing the heat carrier and the coarse char pyrolysis product out of the gravity-fed baffled conduit.

**[0046]** In several embodiments, feeding the heat carrier to the gravity-fed baffled conduit may include feeding the heat carrier and the pyrolysis substrate to the same level in the gravity-fed baffled conduit. Feeding the heat carrier to the gravity-fed baffled conduit may include feeding the heat carrier to the gravity-fed baffled conduit upstream of the pyrolysis substrate. Feeding the heat carrier to the gravity-fed baffled conduit may include feeding the heat carrier to the gravity-fed baffled conduit downstream of the pyrolysis substrate.

**[0047]** In various embodiments, the pyrolysis product mixture may include a gas or vapor pyrolysis product and a fine char pyrolysis product. The method may also include directing the gas or vapor pyrolysis product and the fine char pyrolysis product out of the gravity-fed baffled conduit. The method may also include separating the gas or vapor pyrolysis product from the fine char pyrolysis product. The pyrolysis product mixture may include the heat carrier and a coarse char pyrolysis product. The method may include directing the heat carrier and the coarse char pyrolysis product out of the gravity-fed baffled conduit. The method may also include separating the heat carrier from the coarse char pyrolysis product.



The method may include recycling the heat carrier to form a recycled heat carrier. The method may also include feeding the recycled heat carrier to the gravity-fed baffled conduit.

**[0048]** In several embodiments of the method, separating the heat carrier from the coarse char pyrolysis product may include directing a flow comprising a plurality of particulates along a flow axis. The method may also include separating at least a portion of a first particulate from the plurality of particulates to form a separated portion of the first particulate by directing a gas jet along a cross-flow axis, the cross-flow axis intersecting the flow axis at a cross-flow angle, the cross-flow angle being between about 70° and about 180°. As used herein, the plurality of particulates may include the heat carrier and the coarse char pyrolysis product. As used herein, the first particulate may include the coarse char pyrolysis product

**[0049]** In various embodiments, the gas jet may include a gas temperature of between about 300 °C and about 700 °C. The gas temperature may be a temperature in °C of about 300, 320, 340, 360, 380, 400, 420, 440, 460, 480, 500, 520, 540, 560, 580, 600, 620, 640, 660, 680, or 700, or any range between any two of the preceding temperature values.

**[0050]** In some embodiments, the gas jet may include a gas density (in kilograms per cubic meter) of between about 0.4 and about 1.4. The gas density may have a value (in kilograms per cubic meter) of about 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.1, 1.2, 1.3, or 1.4, or any range between any two of the preceding density values.

**[0051]** In several embodiments, the gas jet may include a gas viscosity (in kilograms per meter-second) of between about  $1 \times 10^{-6}$  and about  $1 \times 10^{-4}$ . For example, the gas viscosity may have a value in  $10^{-5}$  kilograms per meter-second of about 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2, 2.2, 2.4, 2.6, 2.8, 3, 3.25, 3.5, 3.75, 4, 4.5, 5, 5.5, 6, 6.5, 7, 7.5, 8, 8.5, 9, 9.5, or 10, or any range between any two of the preceding gas viscosity values.

[0052] In various embodiments, the gas jet may include a gas flow rate of less than 25 cubic feet per minute. The gas jet may include a gas pressure drop of less than 5 inches of for example, about 1.5 inches of water or less.

[0053] In several embodiments of method **400**, separating at least the portion of the first particulate from the plurality of particulates to form the separated portion of the first particulate further may include directing the separated portion of the first particulate away from the cross-flow axis to a surface of a separator conduit. Method **400** may also include directing the separated portion of the first particulate along the surface for a distance. Directing the separated portion of the first particulate along the surface may include directing the separated portion of the first particulate substantially parallel to the first directional flow axis. Directing the separated portion of the first particulate along the surface may include using the Coandă effect. Some embodiments may include diverting the separated portion of the first particulate along the surface away from the surface to a cross-flow output. Diverting the separated portion of the first particulate along the surface away from the surface and through the cross-flow output may include using the Coandă effect. Diverting the separated portion of the first particulate along the surface away from the surface and through the cross-flow output may include contacting the separated portion of the first particulate along the surface with an entrance vane. The entrance vane may be in fluidic communication with the cross-flow output.

[0054] In various embodiments of method **400**, separating at least the portion of the first particulate from the plurality of particulates may include substantially separating the first particulate from the plurality of particulates. Separating at least the portion of the first particulate from the plurality of particulates may include separating at least about 90%, 95%, 97%, 98%, 99%, 99.1%, 99.2%, 99.3%, 99.4%, 99.5%, 99.6%, 99.7%, 99.8%, 99.9%, 99.95%, 99.99%, 99.995%, or 99.999% by weight of the first particulate from the plurality of

particulates. For example, separating at least the portion of the first particulate from the plurality of particulates may include separating at least about 99% by weight of the first particulate from the plurality of particulates.

**[0055]** In some embodiments, the first particulate may include one or more of a biomass or a pyrolysis product, for example, a biomass pyrolysis product. For example, the first particulate may include char. The first particulate may comprise a first average density (in kilograms per cubic meter) of between about 100 and about 2,000. For example, the first average density (in kilograms per cubic meter) may be about 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1800, 1900, or 2000, or between any two of the preceding density values. For example, the first average density may be about 374 kilograms per cubic meter.

**[0056]** In several embodiments, the first particulate may be characterized by a first average diameter (in millimeters) of between about 0.1 and about 10. For example, the first average diameter (in millimeters) may be about 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.2, 1.4, 1.6, 1.8, 2, 2.25, 2.5, 2.75, 3, 3.25, 3.5, 3.75, or 4, or between any two of the preceding average diameter values.

**[0057]** In various embodiments, the first particulate may include an average flow rate (in kilograms per second) of between about 0.0012 and about 0.0023. For example, the average flow rate (in kilograms per second) may be about 0.0012, 0.0013, 0.0014, 0.0015, 0.0016, 0.0017, 0.0018, 0.0019, 0.0020, 0.0021, 0.0022, or 0.0023, or between any two of the preceding flow rate values.

**[0058]** In some embodiments, the first particulate may include a first average density and the plurality of particulates may include at least a second particulate. The second particulate may be characterized by a second average density greater than the first average density. The second particulate may be, for example, a heat carrier suitable for use in an auger pyrolyzer.

The second particulate may include one or more of a metal, a glass, a ceramic, a mineral, or a polymeric composite. For example, the second particulate may include one or more of: steel, stainless steel, cobalt (Co), molybdenum (Mo), nickel (Ni), titanium (Ti), tungsten (W), zinc (Zn), antimony (Sb), bismuth (Bi), cerium (Ce), vanadium (V), niobium (Nb), tantalum (Ta), chromium (Cr), manganese (Mn), rhenium (Re), iron (Fe), platinum (Pt), iridium (Ir), palladium (Pd), osmium (Os), rhodium (Rh), ruthenium (Ru), nickel, copper impregnated zinc oxide (Cu/ZnO), copper impregnated chromium oxide (Cu/Cr), nickel aluminum oxide (Ni/Al<sub>2</sub>O<sub>3</sub>), palladium aluminum oxide (PdAl<sub>2</sub>O<sub>3</sub>), cobalt molybdenum (CoMo), nickel molybdenum (NiMo), nickel molybdenum tungsten (NiMoW), sulfided cobalt molybdenum (CoMo), sulfided nickel molybdenum (NiMo), or a metal carbide.

**[0059]** In several embodiments, the second average density of the second particulate (in kilograms per cubic meter) may be between about 3,000 and about 23,000, for example, about 3,000, 4,000, 5,000, 6,000, 7,000, 8,000, 9,000, 10,000, 11,000, 12,000, 13,000, 14,000, 15,000, 16,000, 17,000, 18,000, 19,000, 20,000, 21,000, 22,000, or 23,000, or between about any two of the preceding density values. For example, the second particulate may be steel or stainless steel at a density of about 7,500 kilograms per cubic meter.

**[0060]** In various embodiments, the second average density of the second particulate divided by the first average density of the first particulate may be a ratio between about 1.5:1 and about 230:1. For example, the ratio may be about 1.5:1, 2:1, 5:1, 10:1, 15:1, 20:1, 25:1, 50:1, 75:1, 100:1, 125:1, 150:1, 175:1, 200:1, 225:1, 230:1, or a range between about any two of the preceding ratios.

**[0061]** In some embodiments, the second particulate may be characterized by a first average diameter (in millimeters) of between about 0.1 and about 25, for example, about 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19,

20, 21, 22, 23, 24, 25, or a range between about any two of the preceding average diameter values, for example, between about 1 mm and about 10 mm.

[0062] In some embodiments, the second particulate may include a spherical, rounded, or ellipsoid morphology. In some embodiments, the second particulate may include a substantially spherical morphology.

[0063] In several embodiments, the second particulate may include a flow rate (in kilograms per second per each ton per day of biomass processed) of about 0.4 to about 1.4, for example, about 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.1, 1.2, 1.3, 1.4, or a range between any two of the preceding flow rates.

[0064] In some embodiments, the first particulate may be characterized by a first terminal velocity and the second particulate may be characterized by a second terminal velocity. The first and second particulates may be characterized by a ratio of the second terminal velocity to the first terminal velocity of at least about 5:1, 10:1, 15:1, 20:1, 25:1, 30:1, or 35:1.

[0065] In various embodiments, method 400 may also include separating at least a portion of a second particulate in the plurality of particulates from the first particulate. For example, method 400 may include separating substantially all of a second particulate in the plurality of particulates from the first particulate. Method 400 may include separating at least a portion of a second particulate in the plurality of particulates from the first particulate in a direction substantially aligned with the first directional flow axis. The method may also include directing the flow axis downward at a flow angle. The flow angle may be less than 90° from vertically downward. The flow angle may be less than 60° from vertically downward.

[0066] In several embodiments, method 400 may include forming the gas jet by flowing a gas through a first convergent nozzle. The first convergent nozzle may include a first nozzle throat. A cross section of the first nozzle throat may include at least two dissimilar axes. For

example, the first nozzle throat may include an elliptical cross section, a circular cross section, a rectangular cross section, a rounded corner rectangular cross section, a polygonal cross section, a composite or combination thereof, or the like.

**[0067]** In various embodiments, method **400** may also include adapting the flow upstream of the gas jet to a first flow diameter and adapting the flow downstream of the gas jet to a second flow diameter. The first flow diameter may be greater than the second flow diameter. The method may also include adapting the flow between the first flow diameter and the second flow diameter using a transition between the first flow diameter and the second flow diameter. The transition may be substantially aligned with the cross-flow angle. For example, the transition may be substantially perpendicular with respect to the flow axis. The transition may extend between at least a portion of the first flow diameter and at least a portion of the first nozzle throat. At least a portion of the second flow diameter may coincide with at least a portion of the first nozzle throat. The first nozzle throat may be located at the second flow diameter of the separator conduit.

**[0068]** In some embodiments, forming the gas jet may also include flowing the gas through a second nozzle throat upstream of the first nozzle throat.

**[0069]** In several embodiments, separating at least the portion of the first particulate from the plurality of particulates may also include extending an entrance vane into a portion of the flow defined by the second flow diameter. The method may include extending at least a portion of the entrance vane into the flow at least partly in an upstream direction with respect to the first directional flow axis.

**[0070]** In various embodiments of method **400**, separating at least the portion of the first particulate from the plurality of particulates may include directing the separated portion of the first particulate away from the flow axis. The method may include directing the separated

portion of the first particulate away from the flow axis substantially opposite to the gas jet along the cross-flow axis with respect to the first directional flow axis.

[0071] In several embodiments, method **400** may include directing a separated portion of the first particulate away from the flow axis through a third nozzle throat. A cross section of the third nozzle throat may include at least two dissimilar axes. For example, the third nozzle throat may include an elliptical cross section, a circular cross section, a rectangular cross section, a rounded corner rectangular cross section, a polygonal cross section, a composite or combination thereof, or the like. Separating at least the portion of the first particulate from the plurality of particulates may also include directing the separated portion of the first particulate away from the third nozzle throat through an elliptical cross section. For example, the method may include directing the separated portion of the first particulate away from the third nozzle throat through a circular cross section.

[0072] In some embodiments, separating at least the portion of the first particulate from the plurality of particulates further may include directing the separated portion of the first particulate away from the third nozzle throat via an exit conduit axis. The exit conduit axis may intersect the flow axis at an angle. The angle may be greater than 0° and less than 180°. For example, the angle may be between about 90° and less than 180°. In some examples, the exit conduit axis may be within about 30° of vertical.

### PROPHETIC EXAMPLE

[0073] Heated spherical steel shot, about 1 mm in diameter, may be added via inlet **106** into reactor conduit **102**. Ground particulate bio-mass (e.g., a mixture of corn stover and wood particulate) may be added via pyrolysis substrate inlet **110** into reactor conduit **102**. The reactor conduit **102** and the steel shot may be heated to a desired pyrolysis temperature, e.g., 500 °C. The heated steel shot and the bio-mass may fall through the one or more baffles **114** mounted in reactor conduit **102**. The heated steel shot and the bio-mass may mix, and

the bio-mass may pyrolyze to form a pyrolysis mixture including gas or vapor of bio-oil, bio-char, and the heated steel shot. A mixture of fine bio-char and the gas or vapor of bio-oil may be collected at pyrolysis product outlet **112**. A mixture of coarse bio-char and the steel shot may be collected at outlet **108**. The falling bed reactor described in this Example may exhibit effective mixing between the steel shot heat carrier and the bio-mass, similar to the mixing observed in fluidized bed reactors. The falling bed reactor described in this Example may also operate without needing inert gas, similar to the operation of auger reactors.

**[0074]** To the extent that the term “includes” or “including” is used in the specification or the claims, it is intended to be inclusive in a manner similar to the term “comprising” as that term is interpreted when employed as a transitional word in a claim. Furthermore, to the extent that the term “or” is employed (e.g., A or B) it is intended to mean “A or B or both.” When the applicants intend to indicate “only A or B but not both” then the term “only A or B but not both” will be employed. Thus, use of the term “or” herein is the inclusive, and not the exclusive use. See Bryan A. Garner, *A Dictionary of Modern Legal Usage* 624 (2d. Ed. 1995). Also, to the extent that the terms “in” or “into” are used in the specification or the claims, it is intended to additionally mean “on” or “onto.” To the extent that the term “selectively” is used in the specification or the claims, it is intended to refer to a condition of a component wherein a user of the apparatus may activate or deactivate the feature or function of the component as is necessary or desired in use of the apparatus. To the extent that the terms “coupled” or “operatively connected” are used in the specification or the claims, it is intended to mean that the identified components are connected in a way to perform a designated function. To the extent that the term “substantially” is used in the specification or the claims, it is intended to mean that the identified components have the relation or qualities indicated with degree of error as would be acceptable in the subject industry.



[0075] As used in the specification and the claims, the singular forms “a,” “an,” and “the” include the plural unless the singular is expressly specified. For example, reference to “a compound” may include a mixture of two or more compounds, as well as a single compound.

[0076] As used herein, the term “about” in conjunction with a number is intended to include  $\pm 10\%$  of the number. In other words, “about 10” may mean from 9 to 11.

[0077] As used herein, the terms “optional” and “optionally” mean that the subsequently described circumstance may or may not occur, so that the description includes instances where the circumstance occurs and instances where it does not.

[0078] In addition, where features or aspects of the disclosure are described in terms of Markush groups, those skilled in the art will recognize that the disclosure is also thereby described in terms of any individual member or subgroup of members of the Markush group. As will be understood by one skilled in the art, for any and all purposes, such as in terms of providing a written description, all ranges disclosed herein also encompass any and all possible sub-ranges and combinations of sub-ranges thereof. Any listed range can be easily recognized as sufficiently describing and enabling the same range being broken down into at least equal halves, thirds, quarters, fifths, tenths, and the like. As a non-limiting example, each range discussed herein can be readily broken down into a lower third, middle third and upper third, and the like. As will also be understood by one skilled in the art all language such as “up to,” “at least,” “greater than,” “less than,” include the number recited and refer to ranges which can be subsequently broken down into sub-ranges as discussed above. Finally, as will be understood by one skilled in the art, a range includes each individual member. For example, a group having 1-3 cells refers to groups having 1, 2, or 3 cells. Similarly, a group having 1-5 cells refers to groups having 1, 2, 3, 4, or 5 cells, and so forth. While various

aspects and embodiments have been disclosed herein, other aspects and embodiments will be apparent to those skilled in the art.

[0079] As stated above, while the present application has been illustrated by the description of embodiments thereof, and while the embodiments have been described in considerable detail, it is not the intention of the applicants to restrict or in any way limit the scope of the appended claims to such detail. Additional advantages and modifications will readily appear to those skilled in the art, having the benefit of the present application. Therefore, the application, in its broader aspects, is not limited to the specific details, illustrative examples shown, or any apparatus referred to. Departures may be made from such details, examples, and apparatuses without departing from the spirit or scope of the general inventive concept.

[0080] The various aspects and embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope and spirit being indicated by the following claims.

**CLAIMS**

1. A falling bed reactor **100**, comprising:
  - a reactor conduit **102** defining a flow axis **104**;
  - an inlet **106** operatively coupled to receive a heat carrier particulate into the reactor conduit **102**;
  - an outlet **108** operatively coupled to direct the heat carrier particulate out of the reactor conduit **102**;
  - one or more baffles **114** mounted in the reactor conduit **102**.
2. The falling bed reactor **100** of claim 1, comprising:
  - the reactor conduit **102** defining the flow axis **104**;
  - the inlet **106** operatively coupled to receive the heat carrier particulate into the reactor conduit **102**;
  - the outlet **108** operatively coupled to direct the heat carrier particulate out of the reactor conduit **102**;
  - a pyrolysis substrate inlet **110** operatively coupled to receive a pyrolysis substrate into the reactor conduit **102**;
  - a pyrolysis product outlet **112** operatively coupled to direct a pyrolysis product out of the reactor conduit **102**; and
  - the one or more baffles **114** mounted in the reactor conduit **102**, each baffle in the one or more baffles **114** comprising a baffle surface **116**, at least a portion of each baffle surface **116** being at an oblique angle **118** with respect to the flow axis **104**.

3. The falling bed reactor **100** of claim 1, configured to be mounted such that at least a portion of the flow axis **104** is parallel or oblique to a vertically downwards direction.
4. The falling bed reactor **100** of claim 2, configured to be mounted such that at least a portion of the flow axis **104** is parallel or oblique to a vertically downwards direction, and at least a portion of each baffle surface **116** is at the oblique angle **118** with respect to the vertically downwards direction.
5. The falling bed reactor **100** of claim 1, mounted to orient the flow axis **104** in a substantially vertically downwards direction.
6. The falling bed reactor **100** of claim 1, a cross section of the reactor conduit **102** comprising a shape that is one of: polygonal, rounded polygonal, elliptical, circular, or a combination or composite thereof.
7. The falling bed reactor **100** of claim 1, a cross section of the reactor conduit **102** comprising a shape that is one of: rectangular, rounded rectangular, elliptical, circular, or a combination or composite thereof.
8. The falling bed reactor **100** of claim 1, a cross section of the reactor conduit **102** being square.
9. The falling bed reactor **100** of claim 1, one or both of the inlet **106** and the outlet **108** being substantially parallel with one or both of the reactor conduit **102** and the flow axis **104**.
10. The falling bed reactor **100** of claim 1, the inlet **106** being operatively coupled to the reactor conduit **102** upstream of the outlet **108** with respect to the flow axis **104**.
11. The falling bed reactor **100** of claim 1, the inlet **106** being operatively coupled to receive a pyrolysis substrate into the reactor conduit **102**.

12. The falling bed reactor **100** of claim 1, the outlet **108** being operatively coupled to direct a pyrolysis product out of the reactor conduit **102**.

13. The falling bed reactor **100** of claim 1, further comprising:

a pyrolysis substrate inlet **110** operatively coupled to receive a pyrolysis substrate into the reactor conduit **102**; and

a pyrolysis product outlet **112** operatively coupled to direct a pyrolysis product out of the reactor conduit **102**.

14. The falling bed reactor **100** of claim 13, further comprising a fine particulate separator **202**, an input **204** of the fine particulate separator **202** operatively coupled to the pyrolysis product outlet **112** of the falling bed reactor **100** and the fine particulate separator **202** comprising a particulate outlet **206** and a gas or vapor outlet **208**.

15. The falling bed reactor **100** of claim 14, the fine particulate separator **202** comprising one or more of: a settling chamber, a baffle chamber, a cyclonic particle separator, an electrostatic precipitator, a filter, or a scrubber.

16. The falling bed reactor **100** of claim 13, the pyrolysis substrate inlet **110** being operatively coupled to the reactor conduit **102** upstream of the pyrolysis product outlet **112** with respect to the flow axis **104**.

17. The falling bed reactor **100** of claim 13, the pyrolysis substrate inlet **110** being operatively coupled to the reactor conduit **102** upstream of the pyrolysis product outlet **112** with respect to the flow axis **104**.

18. The falling bed reactor **100** of claim 13, the pyrolysis substrate inlet **110** being operatively coupled to the reactor conduit **102** at a same level or downstream of the pyrolysis product outlet **112** with respect to the flow axis **104**.

19. The falling bed reactor **100** of claim 13, the pyrolysis substrate inlet **110** being coincident with the inlet **106**.
20. The falling bed reactor **100** of claim 13, the pyrolysis product outlet **112** being coincident with the inlet **106** or the outlet **108**.
21. The falling bed reactor **100** of claim 1, the one or more baffles **114** extending from an inside wall **130** of the reactor conduit **102** into the reactor conduit **102**.
22. The falling bed reactor **100** of claim 21, the one or more baffles **114** extending from the inside wall **130** to define a cantilevered geometry in the reactor conduit **102**.
23. The falling bed reactor **100** of claim 21, the one or more baffles **114** extending across at least a portion of the reactor conduit **102** between a first portion of the inside wall **130** and a second portion of the inside wall **130**.
24. The falling bed reactor **100** of claim 21, each of the one or more baffles **114** comprising a form of one or more of a rod, a plate, a funnel, a cone, a screen, or a protrusion.
25. The falling bed reactor **100** of claim 21, each of the one or more baffles **114** comprising a form of a rod, the rod having a cross-sectional geometry that is at least in part polygonal, rounded polygonal, circular, elliptical, or a combination or composite thereof.
26. The falling bed reactor **100** of claim 21, each of the one or more baffles **114** comprising a baffle surface **116** positioned to intersect at least a portion of the reactor conduit **102** with respect to the flow axis **104**, at least a portion of the baffle surface **116** comprising a geometry that is one or more of flat or convex.
27. The falling bed reactor **100** of claim 21, each of the one or more baffles **114** comprising a baffle surface **116**, at least a portion of the baffle surface **116** being horizontal with respect to the flow axis **104**.

28. The falling bed reactor **100** of claim 21, each of the one or more baffles **114** comprising a baffle surface **116**, at least a portion of the baffle surface **116** being at an oblique angle **118** with respect to the flow axis **104**.
29. The falling bed reactor **100** of claim 28, the one or more baffles **114** being mounted to place at least the portion of each baffle surface **116** at the oblique angle **118** with respect to the flow axis **104** such that the one or more baffles **114** form a staggered or alternating pattern in the reactor conduit **102**.
30. The falling bed reactor **100** of claim 29, the staggered or alternating pattern of the one or more baffles **114** intersecting the flow axis **104** to provide a tortuous flow path through the one or more baffles **114**.
31. The falling bed reactor **100** of claim 21, each baffle in the one or more baffles **114** being mounted to an inside wall **130** of the reactor conduit **102** to define a free edge **120** of each baffle surface **116** and a mounted edge **122** of each baffle surface **116**.
32. The falling bed reactor **100** of claim 21, each baffle surface **116** in the one or more baffles **114** is substantially at the oblique angle **118** with respect to the flow axis **104**.
33. The falling bed reactor **100** of claim 21, the oblique angle **118** being between about 30° and about 60° with respect to the flow axis **104** such that for each baffle surface **116**, a free edge **120** of the baffle surface **116** is further downstream along the flow axis **104** compared to a mounted edge **122** of the baffle surface **116**.
34. The falling bed reactor **100** of claim 21, further comprising an agitator mechanism **126** configured to agitate at least a portion of the one or more baffles **114** effective to dislodge a particulate on at least a portion of the one or more baffles **114**.

35. The falling bed reactor **100** of claim 1, further comprising a heater **128** configured to cause pyrolysis of a substrate in the falling bed reactor **100** by heating one or both of the falling bed reactor **100** and a heat carrier to be fed into the falling bed reactor **100**.
36. The falling bed reactor **100** of claim 1, being configured to employ the heat carrier comprising one or more of: a metal, a glass, a ceramic, a mineral, or a polymeric composite.
37. The falling bed reactor **100** of claim 1, being configured to employ sand as the heat carrier.
38. The falling bed reactor **100** of claim 1, being configured to employ a particulate catalyst as the heat carrier.
39. A pyrolysis system **200**, comprising:
- a falling bed reactor **100**, comprising:
    - a reactor conduit **102** defining a flow axis **104**;
    - an inlet **106** operatively coupled to receive a heat carrier particulate into the reactor conduit **102**;
    - an outlet **108** operatively coupled to direct the heat carrier particulate out of the reactor conduit **102**;
    - one or more baffles **114** mounted in the reactor conduit **102**; and
    - a cross-flow classifier **3100**, comprising:
      - a separator conduit **3102**;
      - a flow input **3104** and a flow output **3106** in fluidic communication with the separator conduit **3102**, the separator conduit **3102** extending between the flow input **3104** and the flow output **3106** to define a flow axis **3108** along at least a portion of



the separator conduit **3102**, the flow input **3104** being located upstream of the flow output **3106** with respect to the flow axis **3108**; and

a cross-flow input **3114** and a cross-flow output **3116** in fluidic communication with the separator conduit **3102** between the flow input **3104** and the flow output **3106**, the cross-flow input **3114** being located upstream of the cross-flow output **3116** with respect to the flow axis **3108**, the cross-flow input **3114** defining a cross-flow axis **3118** intersecting the flow axis **3108** at a cross-flow angle **3120** between about 70° and about 180° with respect to the flow axis **3108**,

wherein:

the outlet **108** of the falling bed reactor **100** is operatively coupled to the flow input **3104** of the cross-flow classifier **3100**; and

the flow output **3106** of the cross-flow classifier **3100** is operatively coupled to the inlet **108** of the falling bed reactor **100**.

40. The pyrolysis system **200** of claim 39, comprising:

the falling bed reactor **100**, comprising:

the reactor conduit **102** defining a flow axis **104**;

the inlet **106** operatively coupled to receive a heat carrier particulate into the reactor conduit **102**;

the outlet **108** operatively coupled to direct the heat carrier particulate out of the reactor conduit **102**;

a pyrolysis substrate inlet **110** operatively coupled to receive a pyrolysis substrate into the reactor conduit **102**;

a pyrolysis product outlet **112** operatively coupled to direct a pyrolysis product out of the reactor conduit **102**;

the one or more baffles **114** mounted in the reactor conduit **102**, each baffle in the one or more baffles **114** comprising a baffle surface **116**, at least a portion of each baffle surface **116** being at an oblique angle **118** with respect to the flow axis **104**; and

the cross-flow classifier **3100**, comprising:

the separator conduit **3102**;

the flow input **3104** and the flow output **3106** in fluidic communication with the separator conduit **3102**, the separator conduit **3102** extending between the flow input **3104** and the flow output **3106** to define the flow axis **3108** along at least a portion of the separator conduit **3102**, the flow input **3104** being located upstream of the flow output **3106** with respect to the flow axis **3108**; and

the cross-flow input **3114** and the cross-flow output **3116** in fluidic communication with the separator conduit **3102** between the flow input **3104** and the flow output **3106**, the cross-flow input **3114** being located upstream of the cross-flow output **3116** with respect to the flow axis **3108**, the cross-flow input **3114** defining the cross-flow axis **3118** intersecting the flow axis **3108** at a cross-flow angle **3120** between about 70° and about 180° with respect to the flow axis **3108**,

wherein:

the outlet **108** of the falling bed reactor **100** is operatively coupled to the flow input **3104** of the cross-flow classifier **3100**; and

the flow output **3106** of the cross-flow classifier **3100** is operatively coupled to the inlet **108** of the falling bed reactor **100**.

41. The pyrolysis system **200** of claim 39, the outlet **108** of the falling bed reactor **100** being operatively coupled to the flow input **3104** of the cross-flow classifier **3100** via an auger or conveyor **230**.
42. The pyrolysis system **200** of claim 39, the flow output **3106** of the cross-flow classifier **3100** being operatively coupled to the inlet **108** of the falling bed reactor **100** via an auger or conveyor **232**.
43. The pyrolysis system **200** of claim 39, further comprising a fine particulate separator **202**, an input **204** of the fine particulate separator **202** operatively coupled to the pyrolysis product outlet **112** of the falling bed reactor **100** and the fine particulate separator **202** comprising a particulate outlet **206** and a gas or vapor outlet **208**.
44. The pyrolysis system **200** of claim 43, the fine particulate separator **202** comprising one or more of: a settling chamber, a baffle chamber, a cyclonic particle separator, an electrostatic precipitator, a filter, or a scrubber.
45. The pyrolysis system **200** of claim 39, further comprising a coarse particulate separator **212**, an input **214** of the coarse particulate separator **212** operatively coupled to the cross-flow output **3116** of the cross-flow classifier **3100** and the coarse particulate separator **212** comprising a particulate outlet **216** and a gas outlet **218**.
46. The pyrolysis system **200** of claim 45, the coarse particulate separator **212** comprising one or more of: a settling chamber, a baffle chamber, a cyclonic particle separator, an electrostatic precipitator, a filter, or a scrubber.
47. The pyrolysis system **200** of claim 39, further comprising a gas recycle conduit **220**, the gas recycle conduit operatively coupled to receive recycled gas from the gas outlet **218** and the gas recycle conduit **220** operatively coupled to direct the recycled gas to the cross-flow input **3114** of the cross-flow classifier **3100**.

48. The pyrolysis system **200** of claim 47, the gas recycle conduit comprising a fan **222**, the fan **222** configured to draw the recycled gas from the gas outlet **218** via the gas recycle conduit **220** and the fan **222** configured to flow the recycled gas to the cross-flow input **3114** of the cross-flow classifier **3100** via the gas recycle conduit **220**.

49. The pyrolysis system **200** of claim 39, the falling bed reactor **100** comprising the falling bed reactor of any of claims 1-38.

50. The pyrolysis system **200** of claim 39, one or both of the flow input **3114** and the flow output **3116** being substantially aligned with the flow axis **3108** of the separator conduit **3102**.

51. The pyrolysis system **200** of claim 39, the cross-flow input **3114** being operatively coupled to the separator conduit **3102** substantially opposite to the cross-flow output **3116** with respect to the flow axis **3108**.

52. The pyrolysis system **200** of claim 39, being mounted such that the flow axis **3108** points downward at a flow angle **3110**.

53. The pyrolysis system **200** of claim 52, the flow angle **3110** being less than 60° from vertically down.

54. The pyrolysis system **200** of claim 39, the separator conduit **3102** comprising a first flow diameter **3122** between the flow input **3104** and the cross-flow input **3114**, and the separator conduit **3102** comprising a second flow diameter **3124** downstream of the cross-flow input **3114**, the first flow diameter **3122** being greater than the second flow diameter **3124**.

55. The pyrolysis system **200** of claim 54, the separator conduit **3102** comprising a transition **3126** between the first flow diameter **3122** and the second flow diameter **3124**, the transition **3126** being substantially aligned with the cross-flow angle **3120**.

56. The pyrolysis system **200** of claim 54, the separator conduit **3102** comprising a transition **3126** between the first flow diameter **3122** and the second flow diameter **3124**, the transition **3126** being substantially perpendicular with respect to the flow axis **3108**.
57. The pyrolysis system **200** of claim 39, the flow input **3104** being configured to accept a plurality of particulates, at least a first particulate in the plurality of particulates being characterized by a first average density and at least a second particulate in the plurality of particulates being characterized by a second average density greater than the first average density.
58. The pyrolysis system **200** of claim 57, the flow output **3106** being configured to convey at least a portion of the first particulate characterized by the first density out of the separator conduit **3102**.
59. The pyrolysis system **200** of claim 58, the cross-flow output **3116** being configured to convey at least a portion of the second particulate characterized by the second density greater than the first density out of the separator conduit **3102**.
60. The pyrolysis system **200** of claim 39, the cross-flow input **3114** defining a first convergent nozzle **3132** comprising a first nozzle throat **3134**.
61. The pyrolysis system **200** of claim 60, a cross section of the first nozzle throat **3134** comprising at least two dissimilar axes.
62. The pyrolysis system **200** of claim 61, the first nozzle throat **3134** comprising an elliptical cross section, a circular cross section, a rectangular cross section, or a rounded corner rectangular cross section.
63. The pyrolysis system **200** of claim 60, the first nozzle throat **3134** being operatively coupled to a nozzle exit zone, at least a portion of the nozzle exit zone comprising a transition

**3126** between a first flow diameter **3122** of the flow conduit **3108** and the first nozzle throat **3134**.

64. The pyrolysis system **200** of claim 63, at least a portion of the nozzle exit zone comprising a second flow diameter **3124** of the separator conduit **3108**, the transition **3126** being located at an upstream side of the first nozzle throat **3134** and the second flow diameter **3124** being located at a downstream side of the first nozzle throat **3134**.

65. The pyrolysis system **200** of claim 64, the first nozzle throat **3134** being located at the second flow diameter **3124** of the separator conduit **3108**.

66. The pyrolysis system **200** of claim 60, the convergent nozzle **3132** of the cross-flow input **3114** comprising a second nozzle throat **3138**, the first nozzle throat **3134** being located at the cross-flow input **3114** between the second nozzle throat **3138** and the separator conduit **3108**.

67. The pyrolysis system **200** of claim 39, the cross-flow output **3116** defining a second convergent nozzle **3142** comprising a third nozzle throat **3144**.

68. The pyrolysis system **200** of claim 67, a cross section of the third nozzle throat **3144** comprising at least two dissimilar axes.

69. The pyrolysis system **200** of claim 68, the third nozzle throat **3144** comprising an elliptical cross section, a circular cross section, a rectangular cross section, or a rounded corner rectangular cross section.

70. The pyrolysis system **200** of claim 68, the third nozzle throat **3144** being operatively coupled to a nozzle entrance zone **3146**, at least a portion of the nozzle entrance zone **3146** comprising a transition **3148** between a second flow diameter **3124** of the flow conduit **3108** and the third nozzle throat **3144**.

71. The pyrolysis system **200** of claim 68, at least a portion of the nozzle entrance zone **3146** comprising an entrance vane **3150**, the entrance vane **3150** extending into the separator conduit **3102** with respect to the second flow diameter **3124**.

72. The pyrolysis system **200** of claim 71, at least a portion of the entrance vane **3150** extending into the separator conduit **3102** at least partly in an upstream direction with respect to the flow axis **3108**.

73. The pyrolysis system **200** of claim 68, the third nozzle throat **3144** being operatively coupled through a nozzle collector zone to an exit conduit **3154**, one or both of the nozzle collector zone and the conduit **3154** comprising an elliptical cross section.

74. The pyrolysis system **200** of claim 68, the third nozzle throat **3144** being operatively coupled through a nozzle collector zone to an exit conduit **3154**, one or both of the nozzle collector zone and the exit conduit **3154** comprising a circular cross section.

75. The pyrolysis system **200** of claim 68, the third nozzle throat **3144** being operatively coupled to an exit conduit **3154**, the exit conduit **3154** defining an exit conduit axis **3156**, the exit conduit axis **3156** intersecting the flow axis **3108** at an exit angle **3158**, the exit angle **3158** being greater than 0° and less than 180°.

76. The pyrolysis system **200** of claim 75, the exit angle **3158** being between about 90° and less than 180°.

77. The pyrolysis system **200** of claim 76, the exit conduit axis **3156** being within about 30° of vertical.

78. A method **400** for pyrolyzing a substrate, comprising:  
**402** feeding a heat carrier to a gravity-fed baffled conduit;

**404** feeding a pyrolysis substrate to the gravity-fed baffled conduit such that the heat carrier and the pyrolysis substrate mix to form a pyrolysis mixture; and

**406** heating the heat carrier and/or the gravity-fed baffled conduit to pyrolyze the pyrolysis substrate in the pyrolysis mixture to form a pyrolysis product mixture.

79. The method of claim 78, the pyrolysis product mixture comprising a gas or vapor pyrolysis product and a fine char pyrolysis product, further comprising directing the gas or vapor pyrolysis product and the fine char pyrolysis product out of the gravity-fed baffled conduit.

80. The method of claim 79, the pyrolysis product mixture comprising the heat carrier and a coarse char pyrolysis product, further comprising directing the heat carrier and the coarse char pyrolysis product out of the gravity-fed baffled conduit.

81. The method of claim 80, further comprising directing the gas or vapor pyrolysis product and the fine char pyrolysis product out of the gravity-fed baffled conduit at the same level as the heat carrier and the coarse char pyrolysis product.

82. The method of claim 81, further comprising directing the gas or vapor pyrolysis product and the fine char pyrolysis product out of the gravity-fed baffled conduit upstream compared to the heat carrier and the coarse char pyrolysis product.

83. The method of claim 81, further comprising directing the gas or vapor pyrolysis product and the fine char pyrolysis product out of the gravity-fed baffled conduit downstream compared to the heat carrier and the coarse char pyrolysis product.

84. The method of claim 78, the pyrolysis product mixture comprising the heat carrier and a coarse char pyrolysis product, further comprising directing the heat carrier and the coarse char pyrolysis product out of the gravity-fed baffled conduit.



85. The method of claim 78, feeding the heat carrier to the gravity-fed baffled conduit comprises feeding the heat carrier and the pyrolysis substrate to the same level in the gravity-fed baffled conduit.

86. The method of claim 78, feeding the heat carrier to the gravity-fed baffled conduit comprises feeding the heat carrier to the gravity-fed baffled conduit upstream of the pyrolysis substrate.

87. The method of claim 78, feeding the heat carrier to the gravity-fed baffled conduit comprises feeding the heat carrier to the gravity-fed baffled conduit downstream of the pyrolysis substrate.

88. The method of claim 78, the pyrolysis product mixture comprising a gas or vapor pyrolysis product and a fine char pyrolysis product, the method further comprising:

directing the gas or vapor pyrolysis product and the fine char pyrolysis product out of the gravity-fed baffled conduit; and

separating the gas or vapor pyrolysis product from the fine char pyrolysis product

89. The method of claim 78, the pyrolysis product mixture comprising the heat carrier and a coarse char pyrolysis product, the method further comprising:

directing the heat carrier and the coarse char pyrolysis product out of the gravity-fed baffled conduit; and

separating the heat carrier from the coarse char pyrolysis product.

90. The method of claim 78, further comprising:

recycling the heat carrier to form a recycled heat carrier; and

feeding the recycled heat carrier to the gravity-fed baffled conduit.

91. The method of claim 78, wherein separating the heat carrier from the coarse char pyrolysis product comprises:

directing a flow comprising a plurality of particulates along a flow axis; and

separating at least a portion of a first particulate from the plurality of particulates to form a separated portion of the first particulate by directing a gas jet along a cross-flow axis, the cross-flow axis intersecting the flow axis at a cross-flow angle, the cross-flow angle being between about 70° and about 180°,

wherein:

the plurality of particulates comprises the heat carrier and the coarse char pyrolysis product; and

the first particulate comprises the coarse char pyrolysis product

92. The method of claim 91, the cross-flow angle being between about 80° and about 100°.

93. The method of claim 91, the cross-flow axis and the flow axis being substantially perpendicular.

94. The method of claim 91, the gas jet comprising a gas temperature of between about 300 °C and about 700 °C.

95. The method of claim 91, the gas jet comprising a gas density in kilograms per cubic meter of between about 0.4 and about 1.4.

96. The method of claim 91, the gas jet comprising a gas viscosity in kilograms per meter-second of between about  $1 \times 10^{-6}$  and about  $1 \times 10^{-4}$ .

97. The method of claim 91, the gas jet comprising a gas flow rate of less than 25 cubic feet per minute.

98. The method of claim 91, the gas jet comprising a gas pressure drop of less than 5 inches of water.

99. The method of claim 91, wherein separating at least the portion of the first particulate from the plurality of particulates to form the separated portion of the first particulate further comprises:

directing the separated portion of the first particulate away from the cross-flow axis to a surface of a separator conduit; and

directing the separated portion of the first particulate along the surface for a distance.

100. The method of claim 99, wherein directing the separated portion of the first particulate along the surface comprises directing the separated portion of the first particulate substantially parallel to the flow axis.

101. The method of claim 99, wherein directing the separated portion of the first particulate along the surface comprises using the Coandă effect.

102. The method of claim 91, further comprising diverting the separated portion of the first particulate along the surface away from the surface to a cross-flow output.

103. The method of claim 102, wherein diverting the separated portion of the first particulate along the surface away from the surface and through the cross-flow output comprises using the Coandă effect.

104. The method of claim 102, wherein diverting the separated portion of the first particulate along the surface away from the surface and through the cross-flow output comprises contacting the separated portion of the first particulate along the surface with an entrance vane, the entrance vane being in fluidic communication with the cross-flow output.

105. The method of claim 91, wherein separating at least the portion of the first particulate from the plurality of particulates comprises substantially separating the first particulate from the plurality of particulates.

106. The method of claim 91, wherein separating at least the portion of the first particulate from the plurality of particulates comprises separating at least about 99% by weight of the first particulate from the plurality of particulates.

107. The method of claim 91, the first particulate comprising a pyrolysis product.

108. The method of claim 91, the first particulate comprising one or more of a biomass or a biomass pyrolysis product.

109. The method of claim 91, the first particulate comprising char.

110. The method of claim 91, the first particulate being characterized by a first average density in kilograms per cubic meter of between about 100 and about 2,000.

111. The method of claim 91, the first particulate being characterized by a first average diameter in millimeters of between about 0.1 and about 10.

112. The method of claim 91, the first particulate comprising an average flow rate in kilograms per second of between about 0.0012 and about 0.0023.

113. The method of claim 91, the first particulate being characterized by a first average density and the plurality of particulates comprising at least a second particulate characterized by a second average density greater than the first average density.

114. The method of claim 113, the second particulate comprising one or more of a metal, a glass, a ceramic, a mineral, or a polymeric composite.

115. The method of claim 113, the second particulate comprising one or more of: steel, stainless steel, cobalt (Co), molybdenum (Mo), nickel (Ni), titanium (Ti), tungsten (W), zinc

(Zn), antimony (Sb), bismuth (Bi), cerium (Ce), vanadium (V), niobium (Nb), tantalum (Ta), chromium (Cr), manganese (Mn), rhenium (Re), iron (Fe), platinum (Pt), iridium (Ir), palladium (Pd), osmium (Os), rhodium (Rh), ruthenium (Ru), nickel, copper impregnated zinc oxide (Cu/ZnO), copper impregnated chromium oxide (Cu/Cr), nickel aluminum oxide (Ni/Al<sub>2</sub>O<sub>3</sub>), palladium aluminum oxide (PdAl<sub>2</sub>O<sub>3</sub>), cobalt molybdenum (CoMo), nickel molybdenum (NiMo), nickel molybdenum tungsten (NiMoW), sulfided cobalt molybdenum (CoMo), sulfided nickel molybdenum (NiMo), or a metal carbide.

116. The method of claim 113, the second average density of the second particulate in kilograms per cubic meter being between about 3,000 and about 23,000.

117. The method of claim 113, the second average density of the second particulate divided by the first average density of the first particulate being a ratio between about 1.5:1 and about 230:1.

118. The method of claim 113, the second particulate being characterized by a first average diameter in millimeters of between about 1 and about 10.

119. The method of claim 113, the second particulate comprising a spherical, rounded or ellipsoid morphology

120. The method of claim 113, the second particulate comprising a flow rate in kilograms per second of about 0.4 to about 1.4 per each ton per day of biomass processed.

121. The method of claim 113, the first particulate having a first terminal velocity and the second particulate having a second terminal velocity, the first and second particulates being characterized by a ratio of second terminal velocity to first terminal velocity of at least about 5:1.

122. The method of claim 113, the first particulate having a first terminal velocity and the second particulate having a second terminal velocity, the first and second particulates being

characterized by a ratio of second terminal velocity to first terminal velocity of at least about 10:1.

123. The method of claim 113, the first particulate having a first terminal velocity and the second particulate having a second terminal velocity, the first and second particulates being characterized by a ratio of second terminal velocity to first terminal velocity of at least about 20:1.

124. The method of claim 91, further comprising separating at least a portion of a second particulate in the plurality of particulates from the first particulate.

125. The method of claim 91, further comprising separating substantially all of a second particulate in the plurality of particulates from the first particulate.

126. The method of claim 91, further comprising separating at least a portion of a second particulate in the plurality of particulates from the first particulate in a direction substantially aligned with the flow axis.

127. The method of claim 91, further comprising directing the flow axis downward at a flow angle.

128. The method of claim 127, the flow angle being less than 90° from vertically downward.

129. The method of claim 127, the flow angle being less than 60° from vertically downward.

130. The method of claim 91, further comprising forming the gas jet by flowing a gas through a first convergent nozzle comprising a first nozzle throat.

131. The method of claim 91, a cross section of the first nozzle throat comprising at least two dissimilar axes.

132. The method of claim 91, the first nozzle throat comprising an elliptical cross section, a circular cross section, a rectangular cross section, or a rounded corner rectangular cross section.

133. The method of claim 91, further comprising:

adapting the flow upstream of the gas jet to a first flow diameter; and

adapting the flow downstream of the gas jet to a second flow diameter,

the first flow diameter being greater than the second flow diameter.

134. The method of claim 133, further comprising adapting the flow between the first flow diameter and the second flow diameter using a transition between the first flow diameter and the second flow diameter, the transition being substantially aligned with the cross-flow angle.

135. The method of claim 134, further comprising adapting the flow using a transition between the first flow diameter and the second flow diameter, the transition being substantially perpendicular with respect to the flow axis.

136. The method of claim 134, further comprising adapting the flow using a transition between the first flow diameter and the second flow diameter, the transition extending between at least a portion of the first flow diameter and at least a portion of the first nozzle throat.

137. The method of claim 134, at least a portion of the second flow diameter coinciding with at least a portion of the first nozzle throat.

138. The method of claim 137, the first nozzle throat being located at the second flow diameter of the separator conduit.

139. The method of claim 134, forming the gas jet further comprises flowing the gas through a second nozzle throat upstream of the first nozzle throat.

140. The method of claim 134, separating at least the portion of the first particulate from the plurality of particulates further comprises extending an entrance vane into a portion of the flow defined by the second flow diameter.

141. The method of claim 140, further comprising extending at least a portion of the entrance vane into the flow at least partly in an upstream direction with respect to the flow axis.

142. The method of claim 91, wherein separating at least the portion of the first particulate from the plurality of particulates comprises directing the separated portion of the first particulate away from the flow axis substantially opposite to the gas jet along the cross-flow axis with respect to the flow axis.

143. The method of claim 91, wherein separating at least the portion of the first particulate from the plurality of particulates comprises directing the separated portion of the first particulate away from the flow axis substantially opposite to the gas jet along the cross-flow axis with respect to the flow axis.

144. The method of claim 91, wherein separating at least the portion of the first particulate from the plurality of particulates further comprises directing a separated portion of the first particulate away from the flow axis through a third nozzle throat.

145. The method of claim 144, a cross section of the third nozzle throat comprising at least two dissimilar axes.

146. The method of claim 144, the third nozzle throat comprising an elliptical cross section, a circular cross section, a rectangular cross section, or a rounded corner rectangular cross section.



147. The method of claim 144, wherein separating at least the portion of the first particulate from the plurality of particulates further comprises directing the separated portion of the first particulate away from the third nozzle throat through an elliptical cross section.

148. The method of claim 144, wherein separating at least the portion of the first particulate from the plurality of particulates further comprises directing the separated portion of the first particulate away from the third nozzle throat through a circular cross section.

149. The method of claim 144, wherein separating at least the portion of the first particulate from the plurality of particulates further comprises directing the separated portion of the first particulate away from the third nozzle throat via an exit conduit axis, the exit conduit axis intersecting the flow axis at an exit angle, the exit angle being greater than  $0^\circ$  and less than  $180^\circ$ .

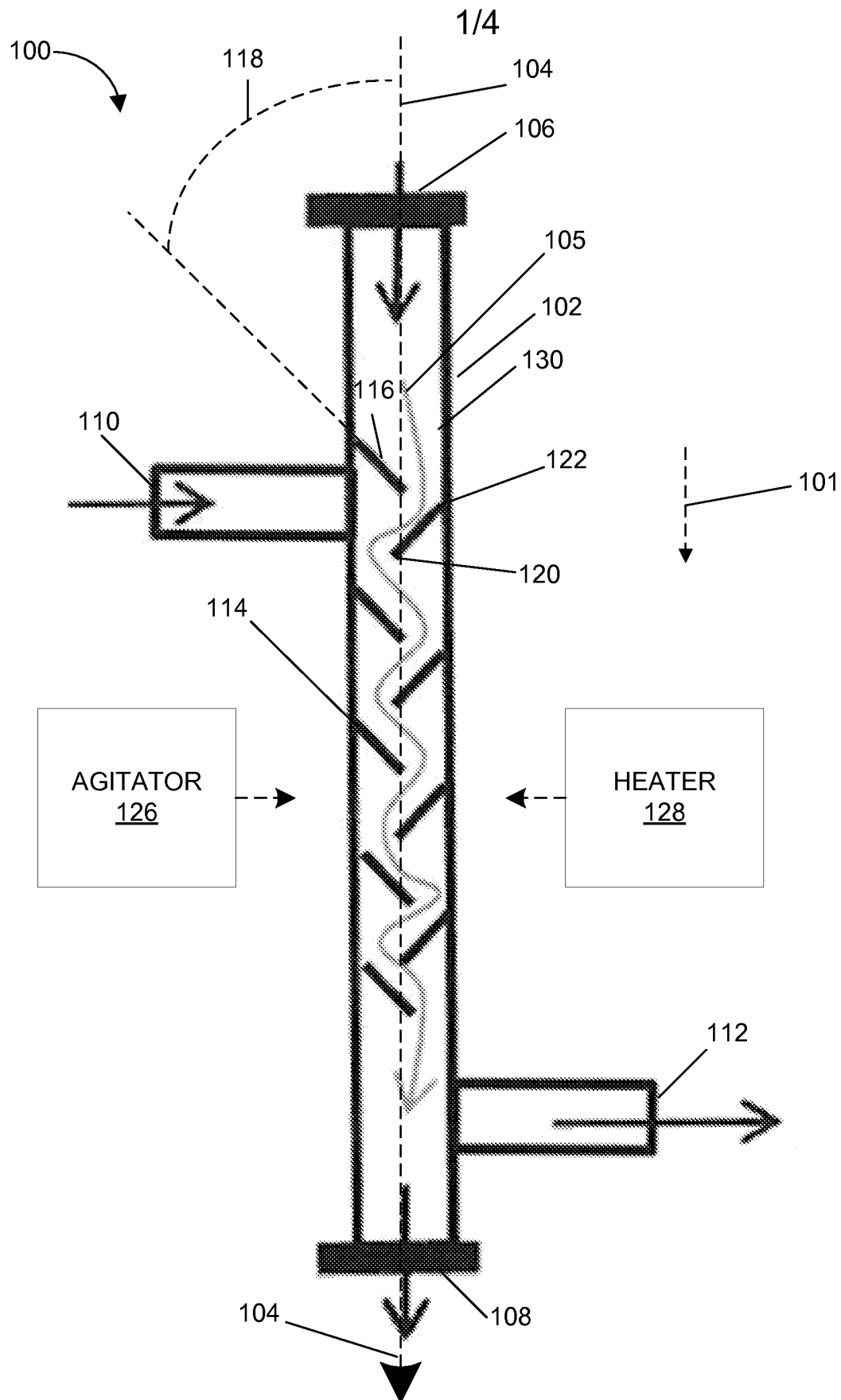


FIG. 1

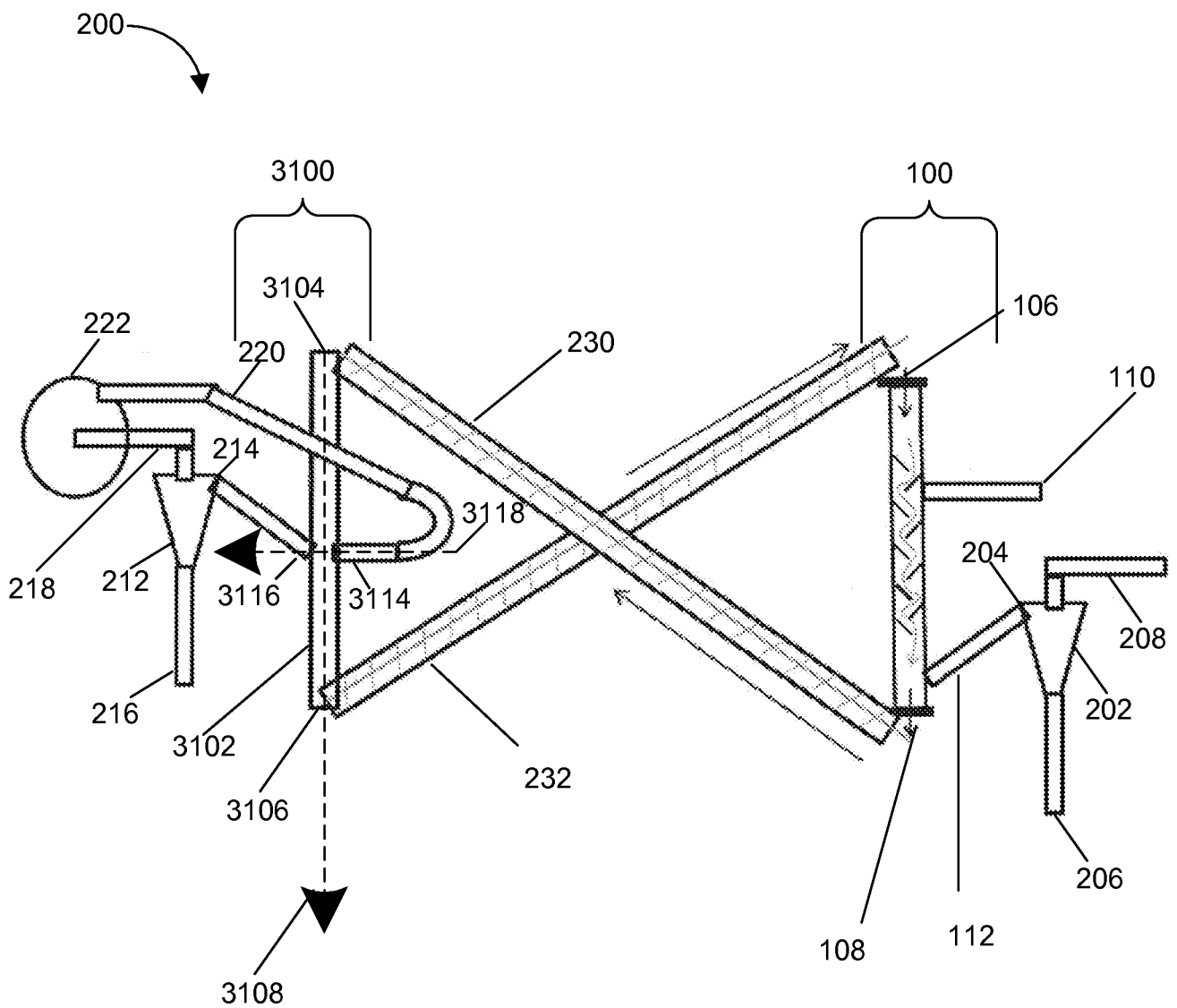


FIG. 2

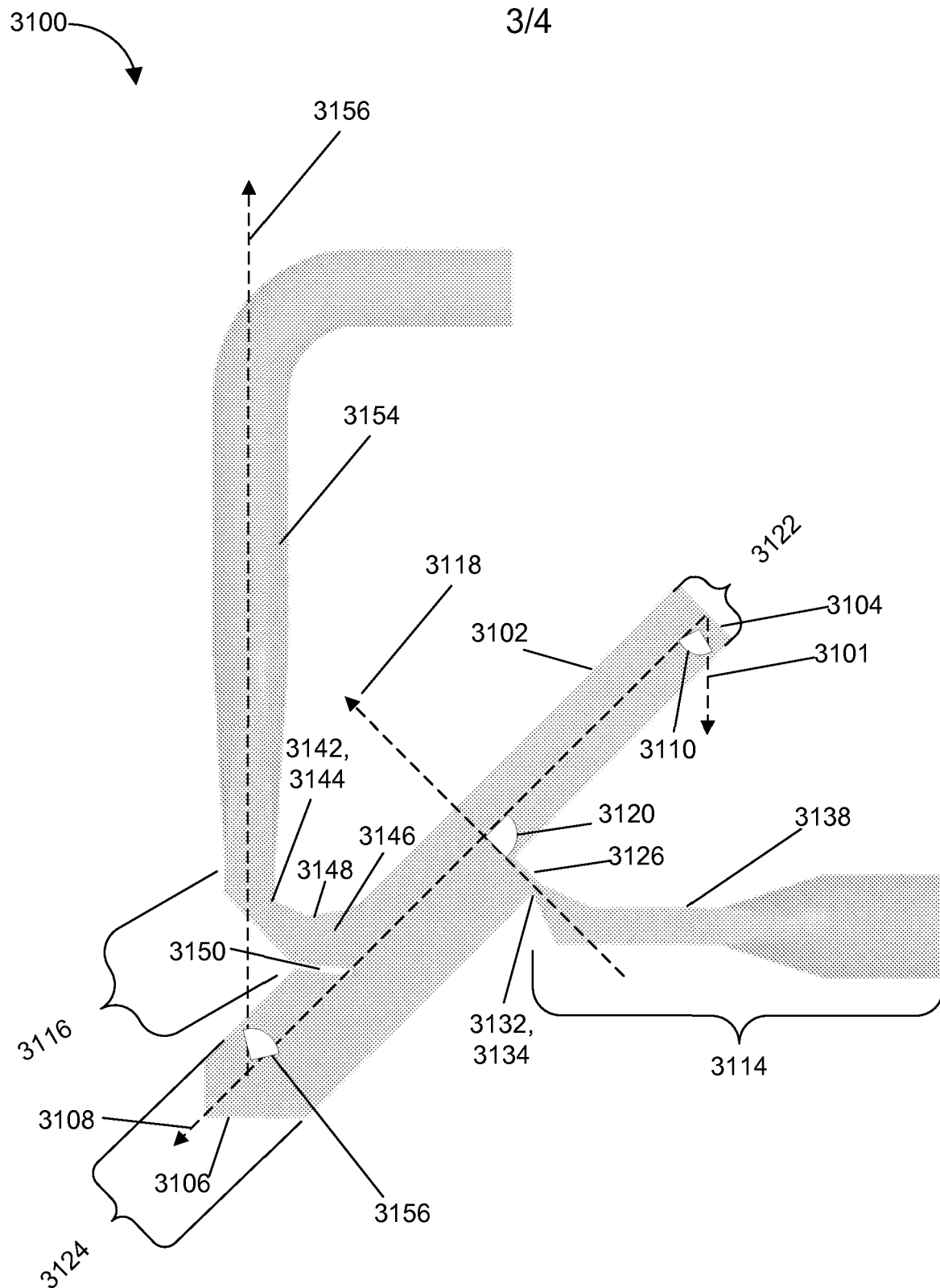


FIG. 3

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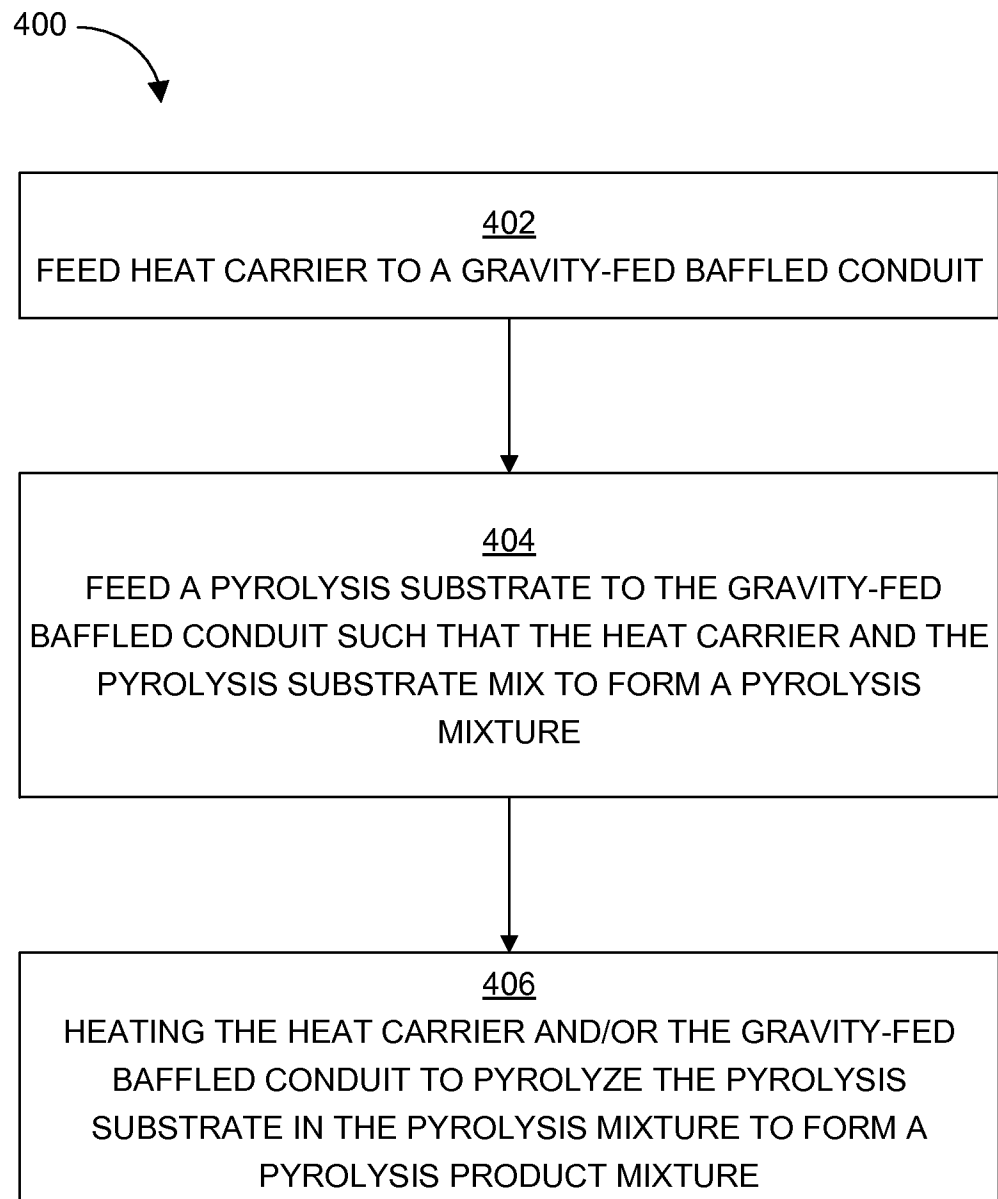


FIG. 4

# INTERNATIONAL SEARCH REPORT

International application No  
PCT/US2014/039443

## A. CLASSIFICATION OF SUBJECT MATTER

INV. B01J19/00 B07B7/086 C10J3/46 C10B49/16 C10G1/02  
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

B01J B07B C10J C10B C10G

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

\* Special categories of cited documents :

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

30 September 2014

Date of mailing of the international search report

08/10/2014

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## INTERNATIONAL SEARCH REPORT

International application No

PCT/US2014/039443

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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