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(54) **Title:** DEVICE AND METHOD FOR CROSS-FLOW SEPARATION

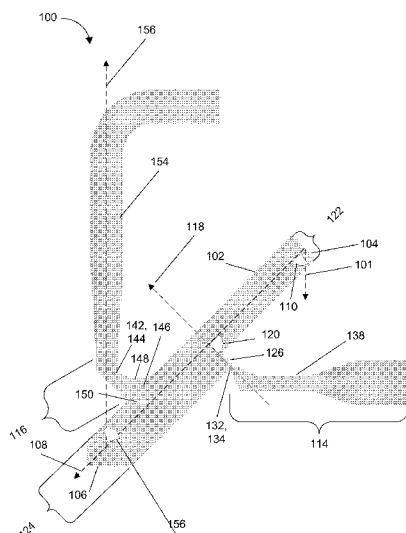


FIG. 1

(57) **Abstract:** The invention relates to a cross-flow classifier and a method for cross-flow classification. The cross-flow classifier (100) comprises a separator conduit (102), a flow input (104) and a flow output (106) in fluid communication with the separator conduit (102), the separator conduit (102) extending between the flow input (104) and the flow output (106) to define a flow axis (108) along at least a portion of the separator conduit (102). The cross-flow classifier (100) further comprises a cross-flow input (114) and a cross-flow output (116) in fluid communication with the separator conduit (102), the cross-flow input (114) defining a cross-flow axis (118) intersecting the flow axis (108) at a cross-flow angle (120) between about 70° and about 180° with respect to the flow axis (108).



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DEVICE AND METHOD FOR CROSS-FLOW SEPARATION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority from U.S. Provisional Patent Application No. 61/833,876, filed on June 11, 2013, which is incorporated by reference herein in its entirety.

BACKGROUND

[0002] Auger-based pyrolysis may be used to process biomass. A reusable heat carrier, e.g., metal shot or a solid catalyst, may be used to heat the biomass and volatilize organic material. After pyrolysis, the heat carrier may be recycled after separation from non-volatile pyrolysis products such as char. Even though the heat carrier may have substantially higher density relative to the char, conventional density-based methods of separation may be inefficient to separate the char from the heat carrier. For example, conventional separators supplied with auger-based pyrolysis systems may be undesirably ineffective at removing char from the heat carrier. Poor char removal may cause undesirable build up, which may require time consuming and/or expensive shutdown of the pyrolysis process to permit char cleanup. The present application therefore appreciates that handling char, for example, in auger based pyrolysis systems, may be a challenging endeavor.

SUMMARY

[0003] In one embodiment, a cross-flow particle classifier is provided. The cross-flow classifier may include a separator conduit, a flow input, and a flow output. The flow input and the flow output may be in fluid 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 also include a cross-flow input and a cross-flow output. The cross-flow input and the cross-flow output may be in fluid

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. The cross-flow angle may be between about 70° and about 180° with respect to the flow axis.

[0004] In another embodiment, a pyrolysis system is provided. The pyrolysis system may include a pyrolyzer. The pyrolyzer may include a substrate input, a heat carrier input, and a pyrolysis output. The pyrolysis system may include a cross-flow classifier, for example, the cross-flow classifier described herein. The cross-flow classifier may include a flow input. The flow input may be in fluid communication with the pyrolysis output.

[0005] In one embodiment, a method for cross-flow separation is provided. The method may include directing a flow including 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 may intersect the flow axis at a cross-flow angle. The cross-flow angle may be between about 70° and about 180°.

[0006] In another embodiment, a pyrolysis method is provided. The pyrolysis method may include pyrolyzing a pyrolysis substrate in contact with a heat carrier to form a pyrolysis product mixture. The pyrolysis product mixture may include a plurality of particulates. The plurality of particulates may include a first particulate and a second particulate. For example, the first particulate may include a pyrolysis product and the second particulate may include the heat carrier. The pyrolysis method may also include separating at least a portion of the first particulate from the plurality of particulates to form a separated portion of the first

particulate. The separating may include the method of cross-flow separation described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] 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.

[0008] FIG. 1 is a block diagram of an example cross-flow particle classifier 100;

[0009] FIG. 2 is a block diagram of an example pyrolysis system 200;

[0010] FIG. 3 is a flow diagram of an example method for cross-flow separation 300;

[0011] FIG. 4 is a flow diagram of an example method of pyrolysis 400;

[0012] FIGS. 5A-5D depict various classifier designs tested in EXAMPLE 1;

[0013] FIG. 6 is a plot of velocity contours along the flow axis, as calculated by model CFD simulations for the example cross-flow particle classifier of FIG. 1; and

[0014] FIG. 7 is an example plot showing particle traces as calculated by model CFD simulations for the example cross-flow particle classifier of FIG. 1.

DETAILED DESCRIPTION

[0015] In several technical fields, particle separators may be used for a variety of purposes. Particle separators may range from separating micron-sized particles in air quality testing to separating immiscible fluids in dryer systems. The instant application describes an efficient char classifier design that, in some embodiments, may operate at better than 99% separation efficiency at moderate gas cross-flow rates.

[0016] FIG. 1 is a block diagram of an example cross-flow particle classifier 100. Cross-flow classifier 100 may include a separator conduit 102, a flow input 104, and a flow output 106. Flow input 104 and flow output 106 may be in fluid communication with separator conduit 102. Separator conduit 102 may extend between flow input 104 and flow output 106 to define a flow axis 108 along at least a portion of separator conduit 102. Flow input 104 may be located upstream of flow output 106 with respect to flow axis 108. Cross-flow classifier 100 may also include a cross-flow input 114 and a cross-flow output 116. Cross-flow input 114 and cross-flow output 116 may be in fluid communication with separator conduit 102 between flow input 104 and flow output 106. Cross-flow input 114 may be located upstream of cross-flow output 116 with respect to flow axis 108. Cross-flow input 114 may define a cross-flow axis 118 intersecting flow axis 108 at a cross-flow angle 120. Cross-flow angle 120 may be between about 70° and about 180° with respect to flow axis 108.

[0017] In various embodiments, one or both of flow input 114 and flow output 116 may be substantially aligned with flow axis 108 of separator conduit 102. In some embodiments, cross-flow input 114 may be coupled to separator conduit 102 substantially opposite to cross-flow output 116 with respect to flow axis 108.

[0018] In some embodiments, cross-flow classifier 100 may be mounted such that the flow axis 108 points downward at a flow angle 110. For example, the flow angle 110 may be less than 90° from vertically downward. In some embodiments, the flow angle 110 may be less than 60° from vertically downward.

[0019] 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 101. “Vertically upward” means antiparallel with respect to the local gravitational acceleration direction. As used herein, “horizontal” means perpendicular to the local gravitational acceleration direction.

[0020] In several embodiments, separator conduit 102 may include a first flow diameter 122 between flow input 104 and cross-flow input 114. Separator conduit 102 may include a second flow diameter 124 downstream of cross-flow input 114. First flow diameter 122 may be greater than second flow diameter 124. Separator conduit 102 may include a transition 126 between first flow diameter 122 and second flow diameter 124. Transition 126 may be substantially aligned with cross-flow angle 120. For example, transition 126 may be substantially perpendicular with respect to flow axis 108.

[0021] In various embodiments, flow input 104 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 less than the first average density. Flow output 106 may be configured to convey at least a portion of the first particulate characterized by the first density out of separator conduit 102. Cross-flow output 116 may be configured to convey at least a portion of the second particulate characterized by the second density less than the first density out of separator conduit 102.

[0022] 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.

[0023] In some embodiments, cross-flow input 114 may define a first convergent nozzle 132. First convergent nozzle 132 may include a first nozzle throat 134. A cross section of first nozzle throat 134 may include at least two dissimilar axes. For example, first nozzle throat 134 may include an elliptical cross section, a rectangular cross section, a rounded corner rectangular cross section, a polygonal cross section, a composite or combination thereof, or the like.

[0024] In several embodiments, first nozzle throat 134 may be coupled to a nozzle exit zone. At least a portion of the nozzle exit zone may include a transition 126 between first flow diameter 122 of flow conduit 108 and first nozzle throat 134. In some embodiments, at least a portion of the nozzle exit zone may include second flow diameter 124 of separator conduit 108. Transition 126 may be located at an upstream side of first nozzle throat 134. Second flow diameter 124 may be located at a downstream side of first nozzle throat 134. First nozzle throat 134 may be located at second flow diameter 124 of separator conduit 108.

[0025] In various embodiments, convergent nozzle 132 of cross-flow input 114 may include a second nozzle throat 138. First nozzle throat 134 may be located at cross-flow input 114 between second nozzle throat 138 and separator conduit 108. Cross-flow output 116 may define a second convergent nozzle 142.

[0026] In some embodiments, second convergent nozzle 142 may include a third nozzle throat 144. A cross section of third nozzle throat 144 may include at least two dissimilar axes. For example, third nozzle throat 144 may include an elliptical 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 144 may be

coupled to a nozzle entrance zone 146. At least a portion of nozzle entrance zone 146 may include a transition 148 between second flow diameter 124 of flow conduit 108 and third nozzle throat 144. In some embodiments, at least a portion of nozzle entrance zone 146 may include an entrance vane 150. Entrance vane 150 may extend into separator conduit 102, for example, with respect to second flow diameter 124. At least a portion of entrance vane 150 may extend into separator conduit 102 at least partly in an upstream direction with respect to flow axis 108. The separator vane 150 may slope downward at least in part along the gravitational direction 101.

[0027] In several embodiments, third nozzle throat 144 may be coupled through a nozzle collector zone to an exit conduit 154. One or both of the nozzle collector zone and conduit 154 may include an elliptical cross section. For example, one or both of the nozzle collector zone and exit conduit 154 may include a circular cross section. Third nozzle throat 144 may be coupled to exit conduit 154. Exit conduit 154 may define an exit conduit axis 156. Exit conduit axis 156 may intersect flow axis 108 at an exit angle 158. Exit angle 158 may be greater than 0° and less than 180°. For example, exit angle 158 may be between about 90° and less than 180°. In some embodiments, exit conduit axis 156 may be within about 30° of vertical.

[0028] FIG. 2 is a block diagram of a pyrolysis system 200. Pyrolysis system 200 may include a pyrolyzer 202. Pyrolyzer 202 may include a substrate input 204, a heat carrier input 206, and a pyrolysis output 208. Pyrolysis system 200 may include a cross-flow classifier, for example, cross flow classifier 100. Cross-flow classifier 100 may include flow input 104. Flow input 104 may be in fluid communication with pyrolysis output 208.

[0029] In various embodiments, pyrolysis system 200 may also include a particle separator 210. The particle separator 210 may be configured to separate a first particulate from a gas. Cross-flow classifier 100 may also include cross-flow output 116 operatively

coupled to provide a mixture of the first particulate and the gas to particle separator **210**. Particle separator **210** 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 some embodiments of pyrolysis system **200**, cross-flow classifier **100** may also include flow output **106**. Flow output **106** may be operatively coupled to deliver a second particulate to heat carrier input **206**. The second particulate may include a heat carrier.

[0031] In several embodiments, cross-flow classifier **100** may include cross-flow input **114** and cross-flow output **116**. Cross-flow output **116** may be operatively coupled to deliver a recycled gas to one or more of pyrolyzer **202**, flow input **104**, and cross-flow input **114**.

[0032] In various embodiments, pyrolyzer **202** may also include an auger (not shown). The auger may be configured to receive a substrate from substrate input **204**. The auger may also be configured to receive a heat carrier from heat carrier input **206**. The auger may also be configured to manipulate the substrate and the heat carrier in pyrolyzer **202** at least in part to pyrolyze the substrate. Pyrolyzer **202** may be an auger pyrolyzer.

[0033] FIG. 3 is a flow diagram of an example method for cross-flow separation **300**. Method **300** may include directing a flow including a plurality of particulates along a flow axis (step **302**). Method **300** 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 (step **304**). The cross-flow axis may intersect the flow axis at a cross-flow angle. The cross-flow angle may be between about 70° and about 180°. For example, the cross-flow angle may be between about 80° and about 100°. In some embodiments, the cross-flow axis and the flow axis may be substantially perpendicular.

[0034] 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.

[0035] 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.

[0036] In several embodiments, the gas jet may include a gas viscosity (in kilograms per meter-second) of between about 1×10^{-6} and about 1×10^{-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.

[0037] 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, for example, about 1.5 inches of water or less.

[0038] In several embodiments of method 300, separating at least the portion of the first particulate from the plurality of particulates to form the separated portion of the first particulate may include directing the separated portion of the first particulate away from the cross-flow axis to a surface of a separator conduit. Method 300 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 fluidically coupled to the cross-flow output.

[0039] In various embodiments of method 300, 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.

[0040] In some embodiments, the first particulate may include one or more of a biomass or a 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.

[0041] 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.

[0042] 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.

[0043] 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, 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), copper impregnated zinc oxide (Cu/ZnO), copper impregnated chromium oxide (Cu/CrO), nickel aluminum oxide (Ni/Al₂O₃), palladium aluminum oxide (PdAl₂O₃), cobalt molybdenum (CoMo), nickel molybdenum (NiMo), nickel molybdenum tungsten (NiMoW), sulfided cobalt molybdenum (CoMo), sulfided nickel molybdenum (NiMo), or a metal carbide.

[0044] 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 any two of the preceding density values. For example, the second particulate may be steel at a density of about 7,500 kilograms per cubic meter.

[0045] 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 10,000:1 and about 30,000:1. For example, the ratio may be about 10,000:1, 12,000:1, 13,000:1, 14,000:1, 15,000:1, 16,000:1, 17,000:1, 18,000:1, 19,000:1, 20,000:1, 22,000:1, 23,000:1, 24,000:1, 25,000:1, 26,000:1, 27,000:1, 28,000:1, 29,000:1, 20,000:1, or between any two of the preceding ratios.

[0046] 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 between any two of the preceding average diameter values.

[0047] 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.

[0048] In several embodiments, the second particulate may include a flow rate (in kilograms per second) of about 0.4 to about 1.4.

[0049] In various embodiments, method 300 may also include separating at least a portion of a second particulate in the plurality of particulates from the first particulate. For example, method 300 may include separating substantially all of a second particulate in the plurality of particulates from the first particulate. Method 300 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.

[0050] In several embodiments, method 300 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 rectangular cross section, a rounded corner rectangular cross section, a polygonal cross section, a composite or combination thereof, or the like.

[0051] In various embodiments, method 300 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. In some embodiments, forming the gas jet may also include flowing the gas through a second nozzle throat upstream of the first nozzle throat.

[0052] 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.

[0053] In various embodiments of method 300, 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.

[0054] In several embodiments, method 300 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 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.

[0055] 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.

[0056] FIG. 4 is a flow diagram of a pyrolysis method 400. Pyrolysis method 400 may include pyrolyzing a pyrolysis substrate in contact with a heat carrier to form a pyrolysis product mixture (step 402). The pyrolysis product mixture may include a plurality of particulates. The plurality of particulates may include a first particulate and a second

particulate. For example, the first particulate may include a pyrolysis product and the second particulate may include the heat carrier. Pyrolysis method **400** may also include separating at least a portion of the first particulate from the plurality of particulates to form a separated portion of the first particulate (step **404**). The separating may include method **300**.

[0057] Pyrolysis method **400** may include forming a recycled heat carrier by separating at least a portion of the second particulate from the plurality of particulates. Pyrolyzing the pyrolysis substrate in contact with the heat carrier may also include contacting the recycled heat carrier to the pyrolysis substrate.

[0058] In various embodiments, the separated portion of the first particulate may include a gas mixed therein. Pyrolysis method **400** may include separating the gas from the separated portion of the first particulate to form a recycled gas.

[0059] In several embodiments, separating at least the portion of the first particulate from the plurality of particulates to form the separated portion of the first particulate may include directing a gas jet along a cross-flow axis. The cross-flow axis may intersect a flow. The flow may include the plurality of particulates along a first directional flow axis. Pyrolysis method **400** may also include forming the gas jet using the recycled gas. For example, pyrolysis method **400** may also include forming at least a portion of the gas jet using the recycled gas.

EXAMPLES

[0060] **EXAMPLE 1:** Computational fluid dynamics (CFD) model simulations were performed (ANSYS Fluent 14.0, ANSYS, Inc., Canonsburg PA) on a range of classifier design configurations, depicted in **FIGS. 5A, 5B, 5C, and 5D**.

[0061] The model simulations used particle tracking with the particle mass and flow conditions as follows. Gas parameters were selected, including temperature of 500 °C,

density of 0.9 kilograms per cubic meter, and gas viscosity of 1.7×10^{-5} kilograms per meter-second. Char particles resulting from pyrolysis were assigned an average density of 370 kilograms per cubic meter. For computation of the model simulations, the char particles were assumed to be approximate parallelepipeds with sizes ranging from (1 mm x 1 mm x 1 mm) to (1 mm x 1 mm x 4 mm). For a 1 ton per day biomass processing system, it was estimated that the mass flow rate of char may be approximately 0.0017 kilograms per second. The steel shot was treated at a density of 7,500 kilograms per cubic meter and a spherical morphology with a diameter of approximately 1 mm. The flow rate of steel shot was estimated to be 0.91 kilograms per second. Due to limitations of an available gas recirculation fan, a gas flow rate of 22.5 cubic feet per minute was determined to be the maximum allowable flow rate in the model CFD simulations. Also in the model CFD simulations, a pressure drop was limited to no more than 1.5 inches of water.

[0062] Referring again to FIGS. 5A, 5B, 5C, and 5D, char and steel shot may enter the classifier at flow input 504 and flow downward due to gravity through separator conduit 502 toward flow output 506. The direction of gravity in the scheme of FIGS. 5A, 5B, 5C, and 5D is indicated by arrow 501. Gas may be introduced at gas input 514 and may intersect the flow of the char and the steel shot in separator conduit 502. The gas flow may entrain a portion of the char and may exit along with the char through char output 516. The shot may exit at flow output 506.

[0063] Surprisingly, the CFD simulations showed that classifier design configurations depicted in FIGS. 5A, 5B, 5C, and 5D exhibited unsatisfactory separation. The CFD simulations showed the gas entering gas input 514 had insufficient momentum to divert the trajectory of the char particles from their original path (flow input 504 to flow output 506) toward char output 516.

[0064] **EXAMPLE 2:** CFD modeling confirmed that the classifier designs shown in FIGS. 5A, 5B, 5C, and 5D were not effective in separating the char from the steel shot.

[0065] Referring to FIG. 1, a converging gas inlet nozzle 114 was arranged to be perpendicular to flow axis 108 of the char and the steel shot. In the example shown in FIG. 1, the shot and char particles fall over a transition ledge 126. The gas may be directed through a rectangular cross-section at nozzle 114 that may be perpendicular to the falling particle trajectory (flow axis 108).

[0066] FIG. 6 is a plot of velocity contours along the flow axis 108, as calculated by model CFD simulations for the design in FIG. 1. The plot in FIG. 6 shows that the nozzle 114 forces the gas jet up against the opposing wall of separator conduit 102. This gas jet follows the contour of the opposing wall of separator conduit 102 at least in part according to the Coandă effect. The gas jet was focused through cross-flow output 116. The gas jet serves to effectively push particles up against the opposing wall of separator conduit 102 as they are entrained on their way to the cross-flow outlet 116.

[0067] The cross-flow outlet 116 includes a nozzle collector zone. The bottom of the nozzle collector zone includes entrance vane 150 that extends into separator conduit 102 in order to increase the capture area. The nozzle collector zone constricts in the third converging nozzle towards the third converging throat 144 to create a more focused and high velocity flow of the gas and the first particulate. The third nozzle throat 144 may function to increase drag on any particles that have made it into the inlet of the collector. As shown by the velocity contours in FIG. 6, nearly the entire channel has high velocity fluid at the third nozzle throat 144. The third nozzle throat 144 transitions from a rectangular duct to a circular duct in exit conduit 154.

[0068] FIG. 7 is an example plot showing particle traces as calculated by model CFD simulations for the design in FIG. 1. In FIG. 7, particles traces are colored by their diameter according to the color bar on the left. Black particle traces represent the second particulate (metal shot). The CFD modeling shows that almost all of the first particulate (char) has been captured in the cross-flow outlet and the second particulate (metal shot) exits in the desired location through the flow output.

[0069] To test the versatility of the final design, a Gaussian distribution of particles was used. The distribution covered particles from (1 mm x 1 mm x 0.1 mm) to (1 mm x 1 mm x 6 mm). Similarly successful results were achieved.

[0070] EXAMPLE 3: An example of the classifier design shown in FIG. 1 was built, put to practice, and tested. Initial testing was done at ambient temperature, and biomass particles were used in place of char. Spherical steel shot of about 1 mm diameter and 7,500 kilograms per cubic meter density was used as the second particulate. Substantially all of the biomass was successfully removed with the example of the classifier design built according to FIG. 1.

[0071] EXAMPLE 4: An example of the classifier design shown in FIG. 1 was built, put to practice and tested. The system was tested at operating temperature of approximately 500 °C, using actual pyrolysis char as the first particulate and spherical steel shot about 1 mm diameter and 7,500 kilograms per cubic meter density as the second particulate. Substantially all of the char was successfully removed with the example of the classifier design built according to FIG. 1.

[0072] 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.

[0073] 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.

[0074] 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.

[0075] 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.

[0076] 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.

[0077] 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.

[0078] 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 cross-flow classifier **100**, comprising:
 - a separator conduit **102**;
 - a flow input **104** and a flow output **106** in fluid communication with the separator conduit **102**, the separator conduit **102** extending between the flow input **104** and the flow output **106** to define a flow axis **108** along at least a portion of the separator conduit **102**, the flow input **104** being located upstream of the flow output **106** with respect to the flow axis **108**; and
 - a cross-flow input **114** and a cross-flow output **116** in fluid communication with the separator conduit **102** between the flow input **104** and the flow output **106**, the cross-flow input **114** being located upstream of the cross-flow output **116** with respect to the flow axis **108**, the cross-flow input **114** defining a cross-flow axis **118** intersecting the flow axis **108** at a cross-flow angle **120** between about 70° and about 180° with respect to the flow axis **108**.
2. The cross-flow classifier of claim 1, one or both of the flow input **114** and the flow output **116** being substantially aligned with the flow axis **108** of the separator conduit **102**.
3. The cross-flow classifier of claim 1, the cross-flow input **114** being coupled to the separator conduit **102** substantially opposite to the cross-flow output **116** with respect to the flow axis **108**.
4. The cross-flow classifier of claim 1, being mounted such that the flow axis **108** points downward at a flow angle **110**.
5. The cross-flow classifier of claim 4, the flow angle **110** being less than 90° from vertically down.

6. The cross-flow classifier of claim 4, the flow angle **110** being less than 60° from vertically down.
7. The cross-flow classifier of claim 1, the separator conduit **102** comprising a first flow diameter **122** between the flow input **104** and the cross-flow input **114**, and the separator conduit **102** comprising a second flow diameter **124** downstream of the cross-flow input **114**, the first flow diameter **122** being greater than the second flow diameter **124**.
8. The cross-flow classifier of claim 7, the separator conduit **102** comprising a transition **126** between the first flow diameter **122** and the second flow diameter **124**, the transition **126** being substantially aligned with the cross-flow angle **120**.
9. The cross-flow classifier of claim 7, the separator conduit **102** comprising a transition **126** between the first flow diameter **122** and the second flow diameter **124**, the transition **126** being substantially perpendicular with respect to the flow axis **108**.
10. The cross-flow classifier of claim 1, the flow input **104** 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 less than the first average density.
11. The cross-flow classifier of claim 10, the flow output **106** being configured to convey at least a portion of the first particulate characterized by the first density out of the separator conduit **102**.
12. The cross-flow classifier of claim 10, the cross-flow output **116** being configured to convey at least a portion of the second particulate characterized by the second density less than the first density out of the separator conduit **102**.

13. The cross-flow classifier of claim 1, the cross-flow input 114 defining a first convergent nozzle 132 comprising a first nozzle throat 134.
14. The cross-flow classifier of claim 13, a cross section of the first nozzle throat 134 comprising at least two dissimilar axes.
15. The cross-flow classifier of claim 13, the first nozzle throat 134 comprising: an elliptical cross section, a rectangular cross section, or a rounded corner rectangular cross section.
16. The cross-flow classifier of claim 13, the first nozzle throat 134 being coupled to a nozzle exit zone, at least a portion of the nozzle exit zone comprising a transition 126 between a first flow diameter 122 of the flow conduit 108 and the first nozzle throat 134.
17. The cross-flow classifier of claim 16, at least a portion of the nozzle exit zone comprising a second flow diameter 124 of the separator conduit 108, the transition 126 being located at an upstream side of the first nozzle throat 134 and the second flow diameter 124 being located at a downstream side of the first nozzle throat 134.
18. The cross-flow classifier of claim 16, the first nozzle throat 134 being located at the second flow diameter 124 of the separator conduit 108.
19. The cross-flow classifier of claim 13, the convergent nozzle 132 of the cross-flow input 114 comprising a second nozzle throat 138, the first nozzle throat 134 being located at the cross-flow input 114 between the second nozzle throat 138 and the separator conduit 108.
20. The cross-flow classifier of claim 1, the cross-flow output 116 defining a second convergent nozzle 142 comprising a third nozzle throat 144.
21. The cross-flow classifier of claim 20, a cross section of the third nozzle throat 144 comprising at least two dissimilar axes.

22. The cross-flow classifier of claim 20, the third nozzle throat **144** comprising: an elliptical cross section, a rectangular cross section, or a rounded corner rectangular cross section.
23. The cross-flow classifier of claim 20, the third nozzle throat **144** being coupled to a nozzle entrance zone **146**, at least a portion of the nozzle entrance zone **146** comprising a transition **148** between a second flow diameter **124** of the flow conduit **108** and the third nozzle throat **144**.
24. The cross-flow classifier of claim 20, at least a portion of the nozzle entrance zone **146** comprising an entrance vane **150**, the entrance vane **150** extending into the separator conduit **102** with respect to the second flow diameter **124**.
25. The cross-flow classifier of claim 24, at least a portion of the entrance vane **150** extending into the separator conduit **102** at least partly in an upstream direction with respect to the flow axis **108**.
26. The cross-flow classifier of claim 20, the third nozzle throat **144** being coupled through a nozzle collector zone to an exit conduit **154**, one or both of the nozzle collector zone and the conduit **154** comprising an elliptical cross section.
27. The cross-flow classifier of claim 20, the third nozzle throat **144** being coupled through a nozzle collector zone to an exit conduit **154**, one or both of the nozzle collector zone and the exit conduit **154** comprising a circular cross section.
28. The cross-flow classifier of claim 20, the third nozzle throat **144** being coupled to an exit conduit **154**, the exit conduit **154** defining an exit conduit axis **156**, the exit conduit axis **156** intersecting the flow axis **108** at an exit angle **158**, the exit angle **158** being greater than 0° and less than 180°.

29. The cross-flow classifier of claim 28, the exit angle **158** being between about 90° and less than 180°.

30. The cross-flow classifier of claim 28, the exit conduit axis **156** being within about 30° of vertical.

31. A pyrolysis system **200**, comprising:

a pyrolyzer **202** comprising a substrate input **204**, a heat carrier input **206**, and a pyrolysis output **208**;

a cross-flow classifier **100** according to any of claims 1-30, the cross-flow classifier **100** comprising a flow input **104**, the flow input **104** being fluidically coupled to the pyrolysis output **208**.

32. The pyrolysis system of claim 31, the cross-flow classifier **100** further comprising a flow output **106**, the flow output **106** being operatively coupled to deliver a second particulate comprising a recycled heat carrier to the heat carrier input **206**.

33. The pyrolysis system of claim 31, further comprising a particle separator **210** configured to separate a first particulate from a gas, the cross-flow classifier **100** further comprising a cross-flow output **116** operatively coupled to provide a mixture of the first particulate and the gas to the particle separator **210**.

34. The pyrolysis system of claim 31, the particle separator **210** comprising one or more of: a settling chamber, a baffle chamber, a cyclonic particle separator, an electrostatic precipitator, a filter, or a scrubber.

35. The pyrolysis system of claim 31, the cross-flow classifier **100** further comprising a cross-flow input **114** and a cross-flow output **116**, the cross-flow output **116** being

operatively coupled to deliver a recycled gas to one or more of the pyrolyzer **202**, the flow input **104**, or the cross-flow input **114**.

36. The pyrolysis system of claim 31, the pyrolyzer **202** further comprising an auger **212**, the auger **212** being configured to:

receive a substrate from the substrate input **204**;

receive a heat carrier from the heat carrier input **206**; and

manipulate the substrate and the heat carrier in the pyrolyzer **202** at least in part to pyrolyze the substrate,

whereby the pyrolyzer **202** is an auger pyrolyzer.

37. A method for cross-flow separation, the method comprising:

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°.

38. The method of claim 37, the cross-flow angle being between about 80° and about 100°.

39. The method of claim 37, the cross-flow axis and the flow axis being substantially perpendicular.

40. The method of claim 37, the gas jet comprising a gas temperature of between about 300 °C and about 700 °C.

41. The method of claim 37, the gas jet comprising a gas density in kilograms per cubic meter of between about 0.4 and about 1.4.

42. The method of claim 37, the gas jet comprising a gas viscosity in kilograms per meter-second of between about 1×10^{-6} and about 1×10^{-4} .

43. The method of claim 37, the gas jet comprising a gas flow rate of less than 25 cubic feet per minute.

44. The method of claim 37, the gas jet comprising a gas pressure drop of less than 5 inches of water.

45. The method of claim 37, 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.

46. The method of claim 45, 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.

47. The method of claim 45, wherein directing the separated portion of the first particulate along the surface comprises using the Coandă effect.

48. The method of claim 37, further comprising diverting the separated portion of the first particulate along the surface away from the surface to a cross-flow output.

49. The method of claim 48, 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.
50. The method of claim 48, 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 **150**, the entrance vane being fluidically coupled to the cross-flow output.
51. The method of claim 37, 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.
52. The method of claim 37, 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.
53. The method of claim 37, the first particulate comprising a pyrolysis product.
54. The method of claim 37, the first particulate comprising one or more of a biomass or a biomass pyrolysis product.
55. The method of claim 37, the first particulate comprising char.
56. The method of claim 37, the first particulate being characterized by a first average density in kilograms per cubic meter of between about 100 and about 2,000.
57. The method of claim 37, the first particulate being characterized by a first average diameter in millimeters of between about 0.1 and about 10.
58. The method of claim 37, the first particulate comprising an average flow rate in kilograms per second of between about 0.0012 and about 0.0023.

59. The method of claim 37, 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 less than the first average density.

60. The method of claim 59, the second particulate comprising one or more of a metal, a glass, a ceramic, a mineral, or a polymeric composite.

61. The method of claim 59, the second particulate comprising one or more of: 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), copper impregnated zinc oxide (Cu/ZnO), copper impregnated chromium oxide (Cu/CrO), nickel aluminum oxide (Ni/Al₂O₃), palladium aluminum oxide (PdAl₂O₃), cobalt molybdenum (CoMo), nickel molybdenum (NiMo), nickel molybdenum tungsten (NiMoW), sulfided cobalt molybdenum, sulfided nickel molybdenum, or a metal carbide.

62. The method of claim 59, the second average density of the second particulate in kilograms per cubic meter being between about 3,000 and about 23,000.

63. The method of claim 59, the second average density of the second particulate divided by the first average density of the first particulate being a ratio between about 10,000:1 and about 30,000:1.

64. The method of claim 59, the second particulate being characterized by a first average diameter in millimeters of between about 0.1 and about 25.

65. The method of claim 59, the second particulate comprising a spherical, rounded or ellipsoid morphology.

66. The method of claim 59, the second particulate comprising a flow rate in kilograms per second of about 0.4 to about 1.4.
67. The method of claim 37, further comprising separating at least a portion of a second particulate in the plurality of particulates from the first particulate.
68. The method of claim 37, further comprising separating substantially all of a second particulate in the plurality of particulates from the first particulate.
69. The method of claim 37, 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.
70. The method of claim 37, further comprising directing the flow axis downward at a flow angle.
71. The method of claim 70, the flow angle being less than 90° from vertically downward.
72. The method of claim 70, the flow angle being less than 60° from vertically downward.
73. The method of claim 37, further comprising forming the gas jet by flowing a gas through a first convergent nozzle comprising a first nozzle throat.
74. The method of claim 73, a cross section of the first nozzle throat comprising at least two dissimilar axes.
75. The method of claim 73, the first nozzle throat comprising an elliptical cross section, a rectangular cross section, or a rounded corner rectangular cross section.
76. The method of claim 37, 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.

77. The method of claim 76, 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.

78. The method of claim 77, 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.

79. The method of claim 77, 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.

80. The method of claim 77, at least a portion of the second flow diameter coinciding with at least a portion of the first nozzle throat.

81. The method of claim 80, the first nozzle throat being located at the second flow diameter of the separator conduit.

82. The method of claim 77, forming the gas jet further comprises flowing the gas through a second nozzle throat upstream of the first nozzle throat.

83. The method of claim 77, 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.

84. The method of claim 83, 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.

85. The method of claim 37, 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.

86. The method of claim 37, 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.

87. The method of claim 37, 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.

88. The method of claim 87, a cross section of the third nozzle throat comprising at least two dissimilar axes.

89. The method of claim 87, the third nozzle throat comprising an elliptical cross section, a rectangular cross section, or a rounded corner rectangular cross section.

90. The method of claim 87, 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.

91. The method of claim 87, 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.

92. The method of claim 87, 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° and less than 180°.

93. A pyrolysis method, the method comprising:

pyrolyzing a pyrolysis substrate in contact with a heat carrier to form a pyrolysis product mixture comprising a plurality of particulates, the plurality of particulates comprising a first particulate and a second particulate, the first particulate comprising a pyrolysis product and the second particulate comprising the heat carrier; and

separating at least a portion of the first particulate from the plurality of particulates to form a separated portion of the first particulate according to the method of cross-flow separation of any of claims 37-92.

94. The method of claim 93, further comprising forming a recycled heat carrier by separating at least a portion of the second particulate from the plurality of particulates according to any of claims 37-92; and

pyrolyzing the pyrolysis substrate in contact with the heat carrier further comprises contacting the recycled heat carrier to the pyrolysis substrate.

95. The method of claim 93, the separated portion of the first particulate comprising a gas mixed therein, further comprising separating the gas from the separated portion of the first particulate to form a recycled gas.

96. The method of claim 95, wherein separating at least the portion of the first particulate from the plurality of particulates to form the separated portion of the first particulate comprises directing a gas jet along a cross-flow axis, the cross-flow axis intersecting a flow comprising the plurality of particulates along a flow axis, further comprising forming the gas jet comprising the recycled gas.

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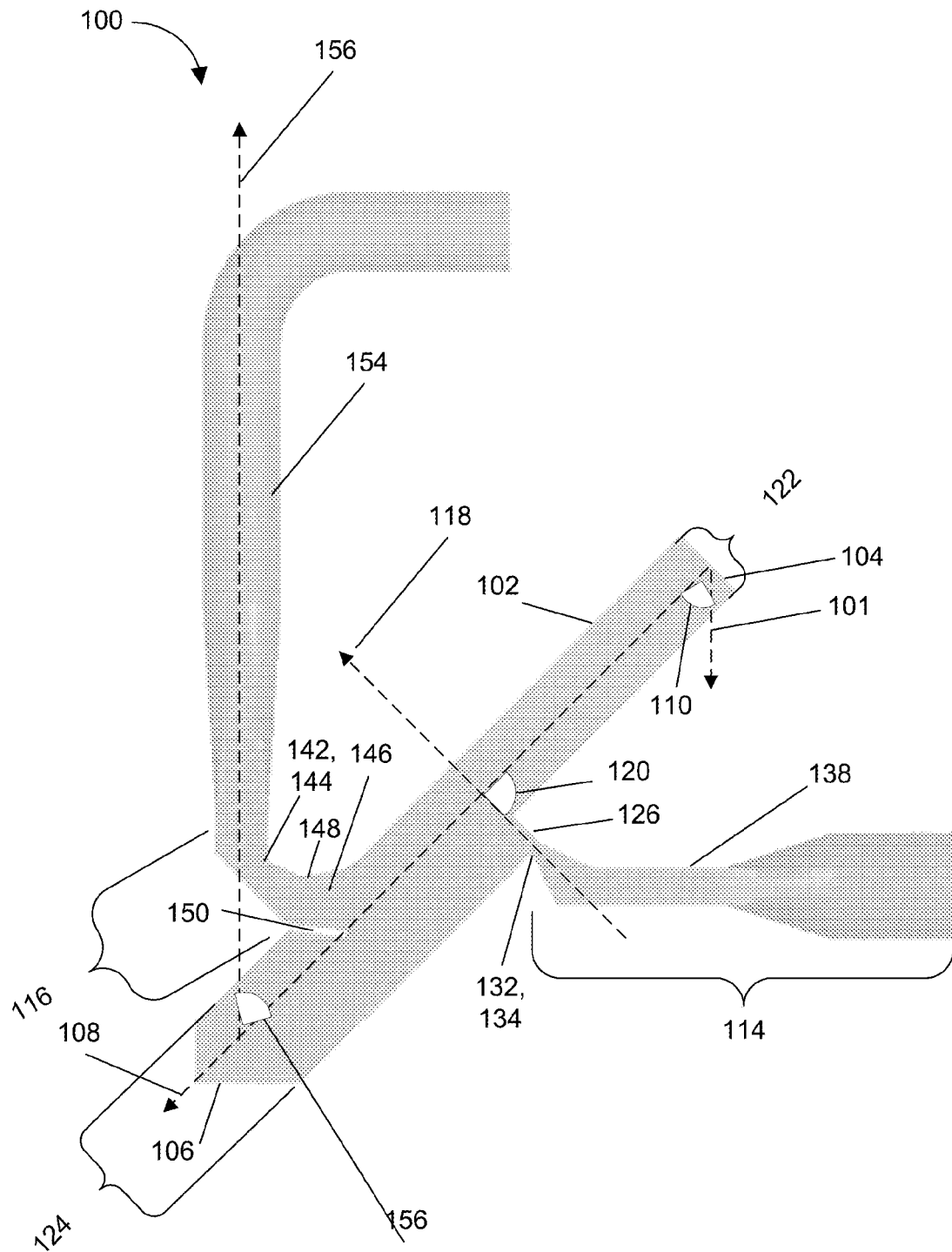


FIG. 1

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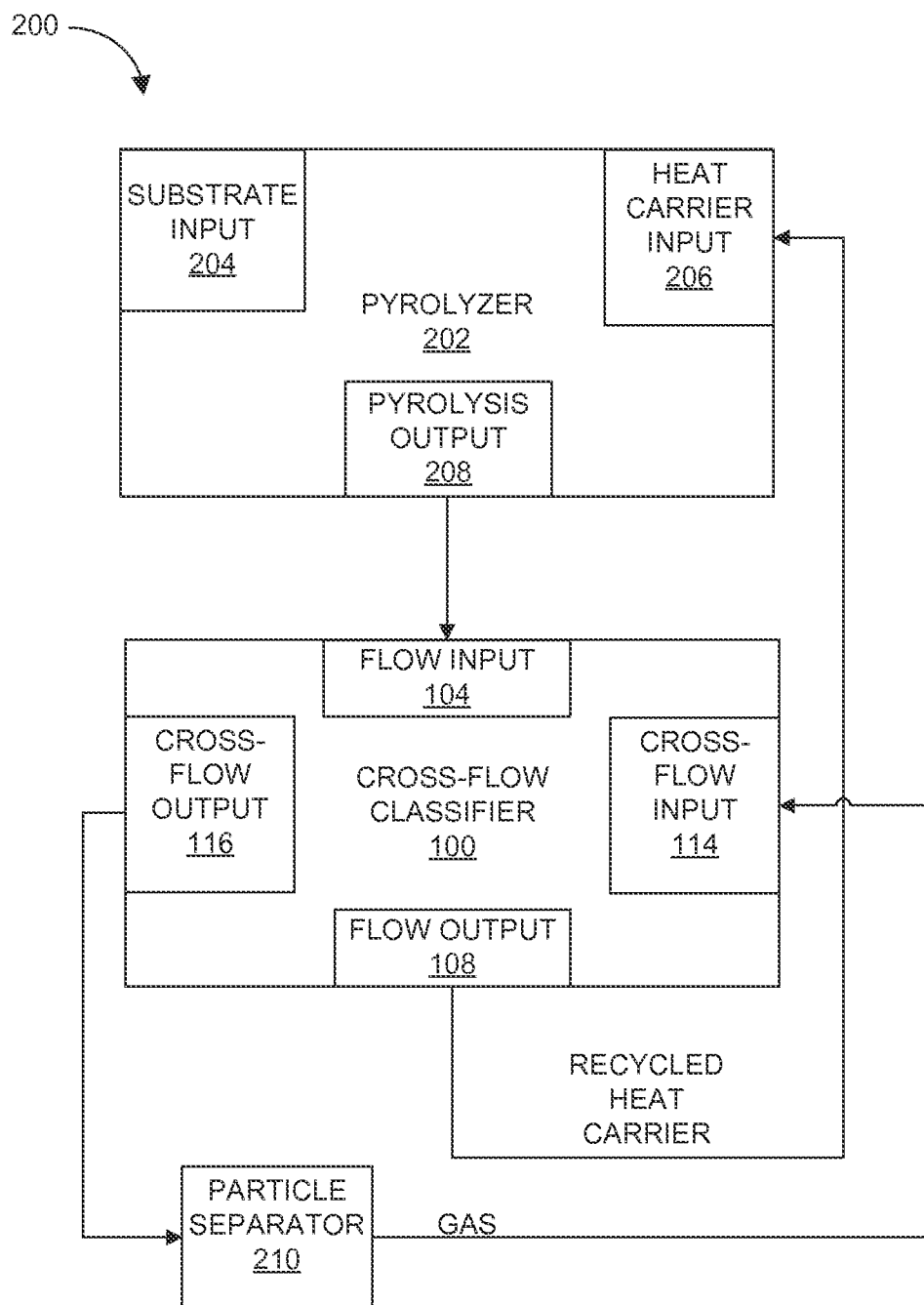


FIG. 2

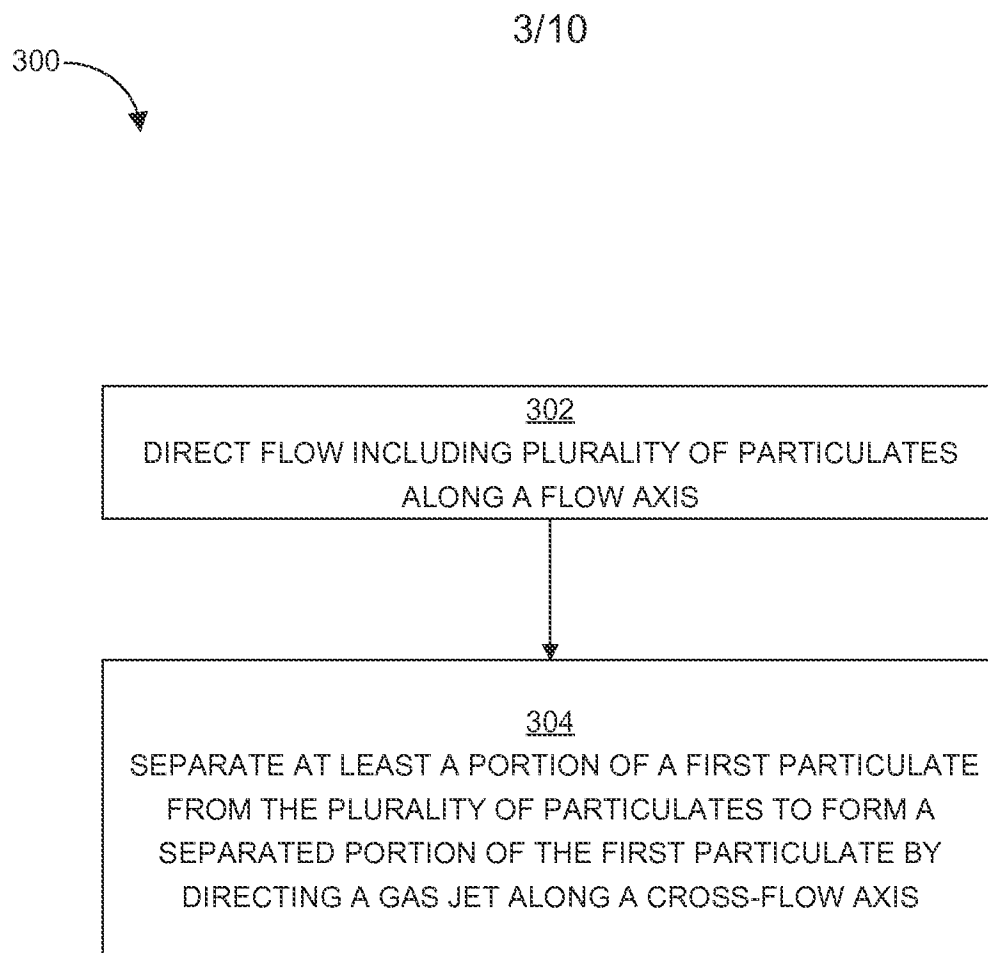


FIG. 3

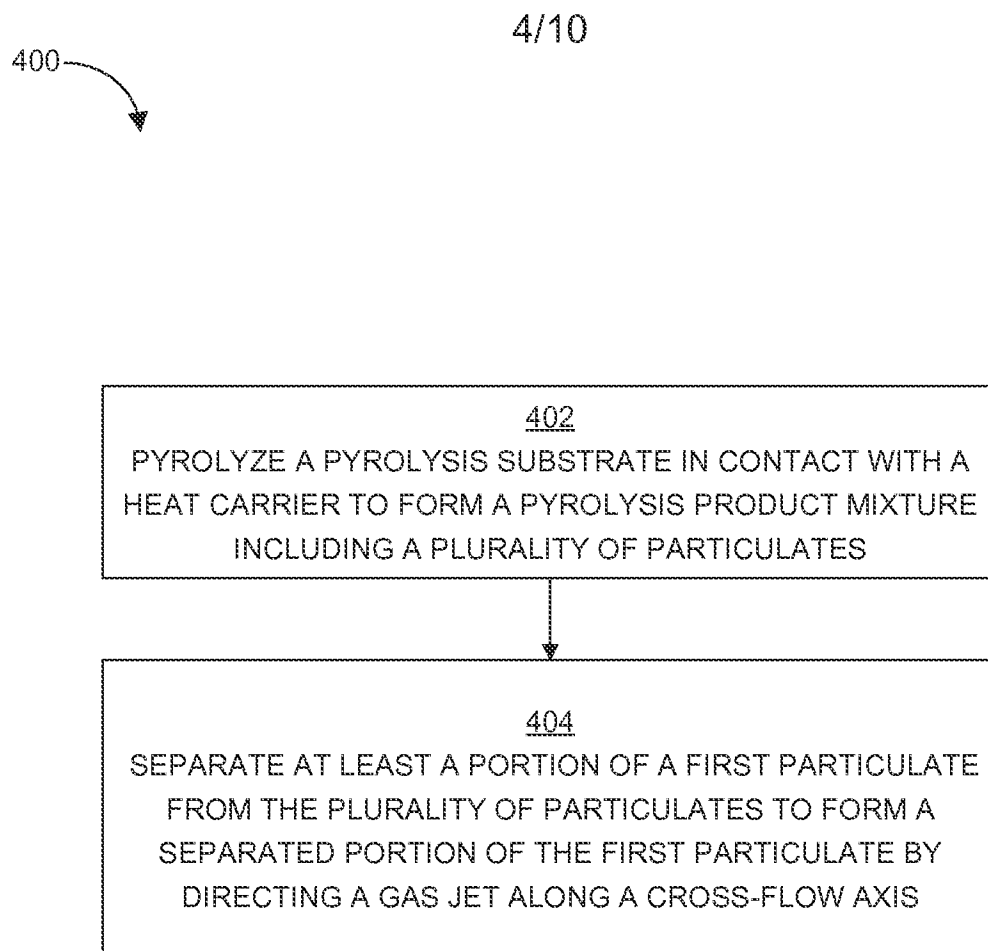
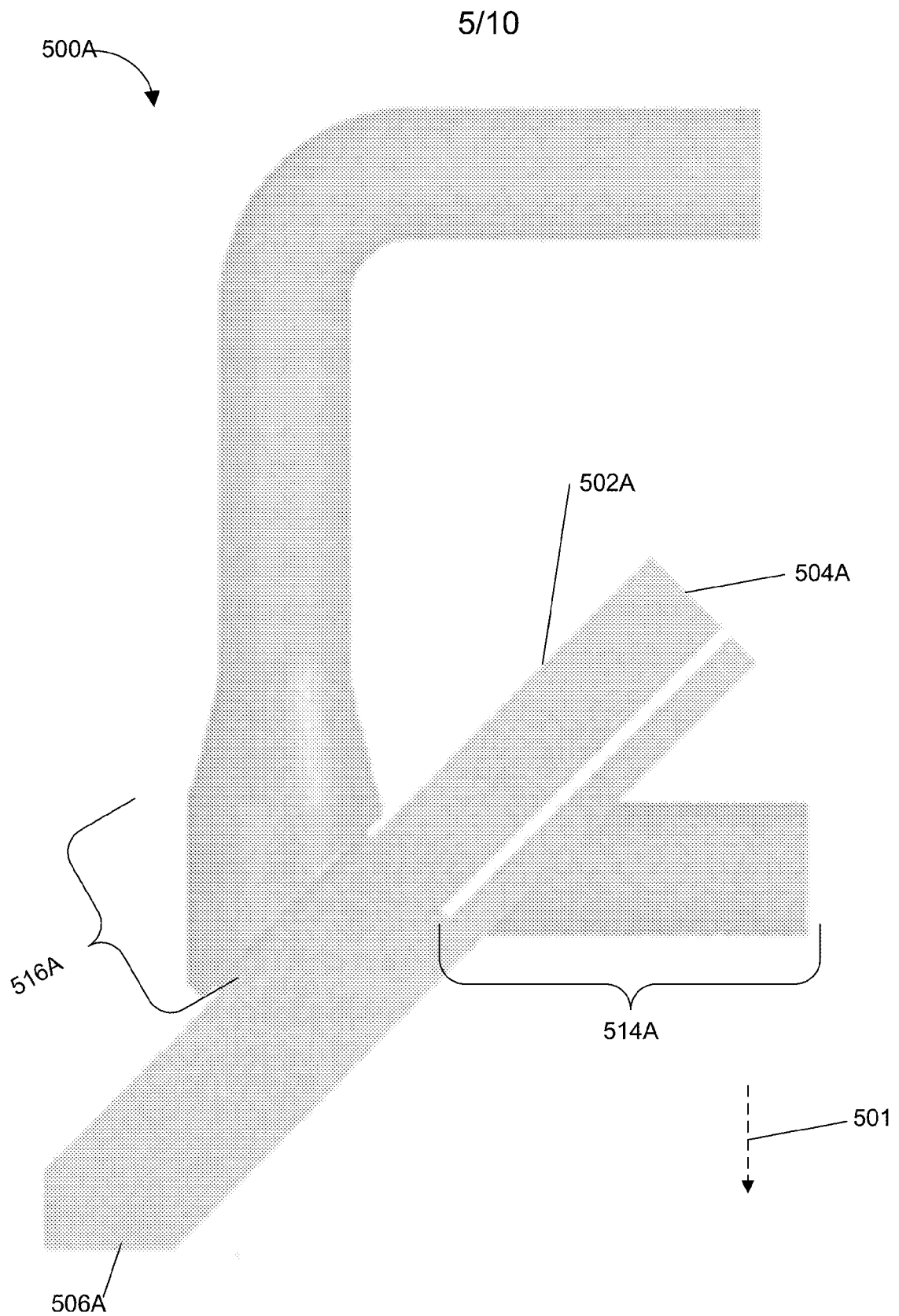


FIG. 4



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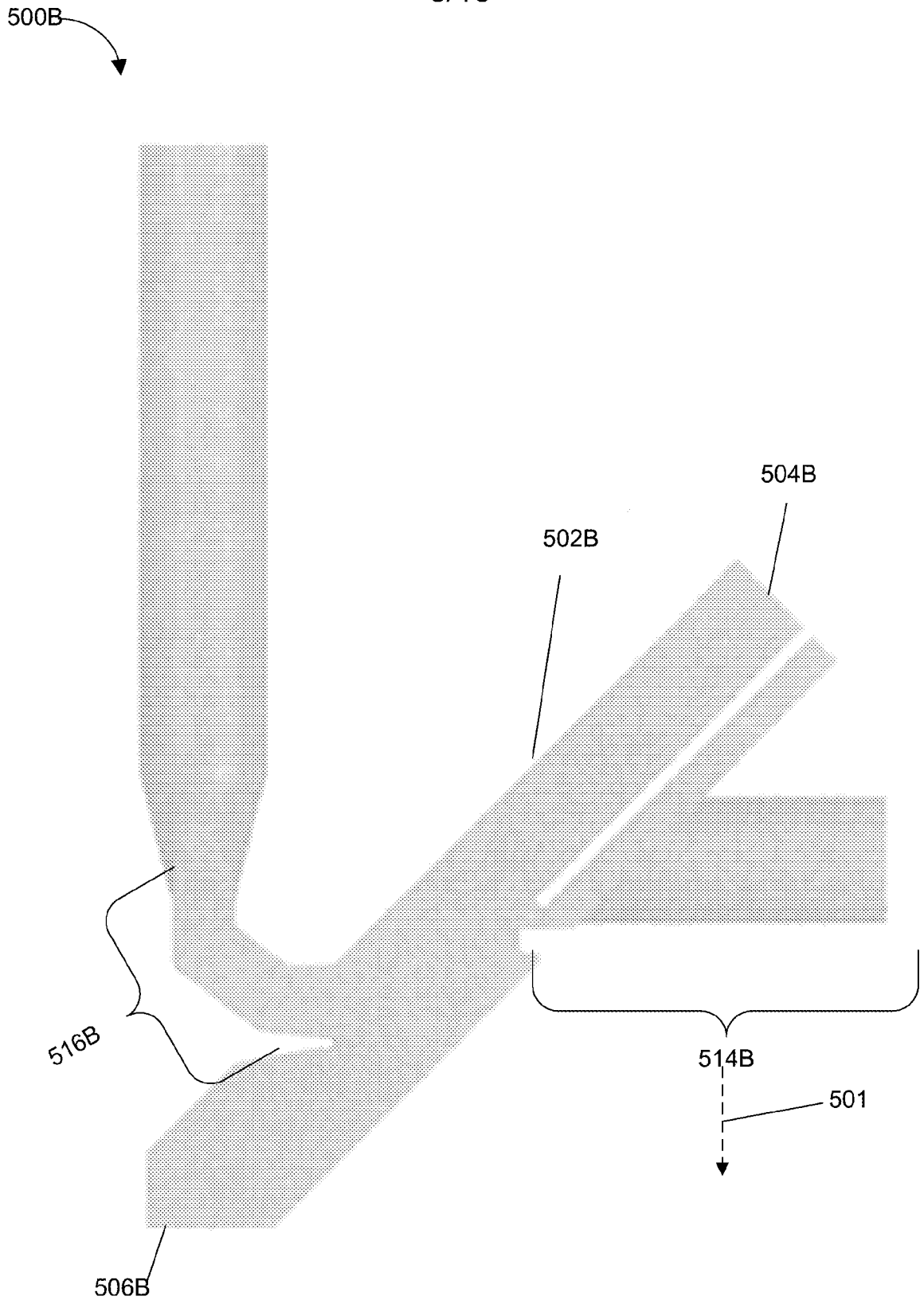


FIG. 5B

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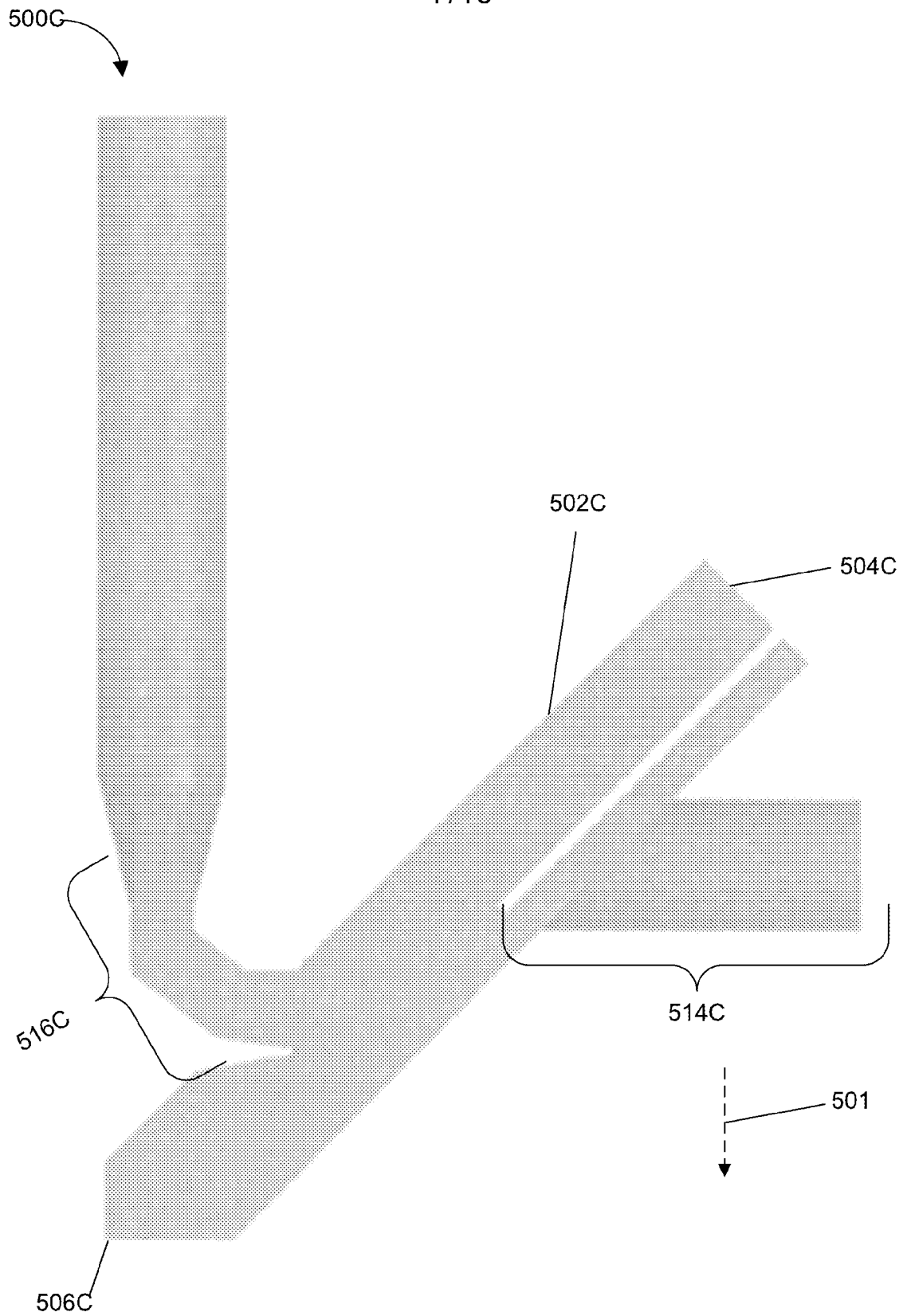


FIG. 5C

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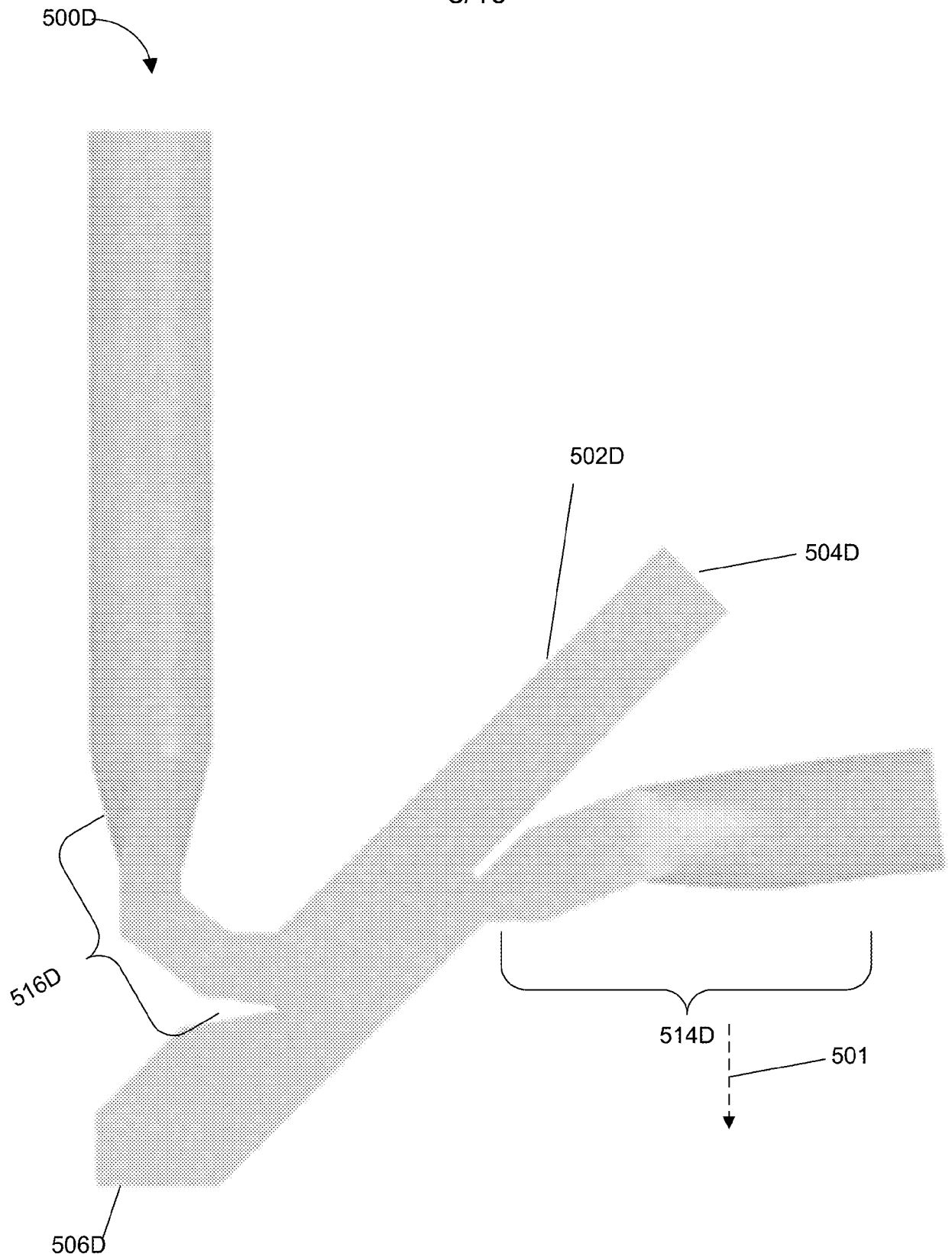


FIG. 5D

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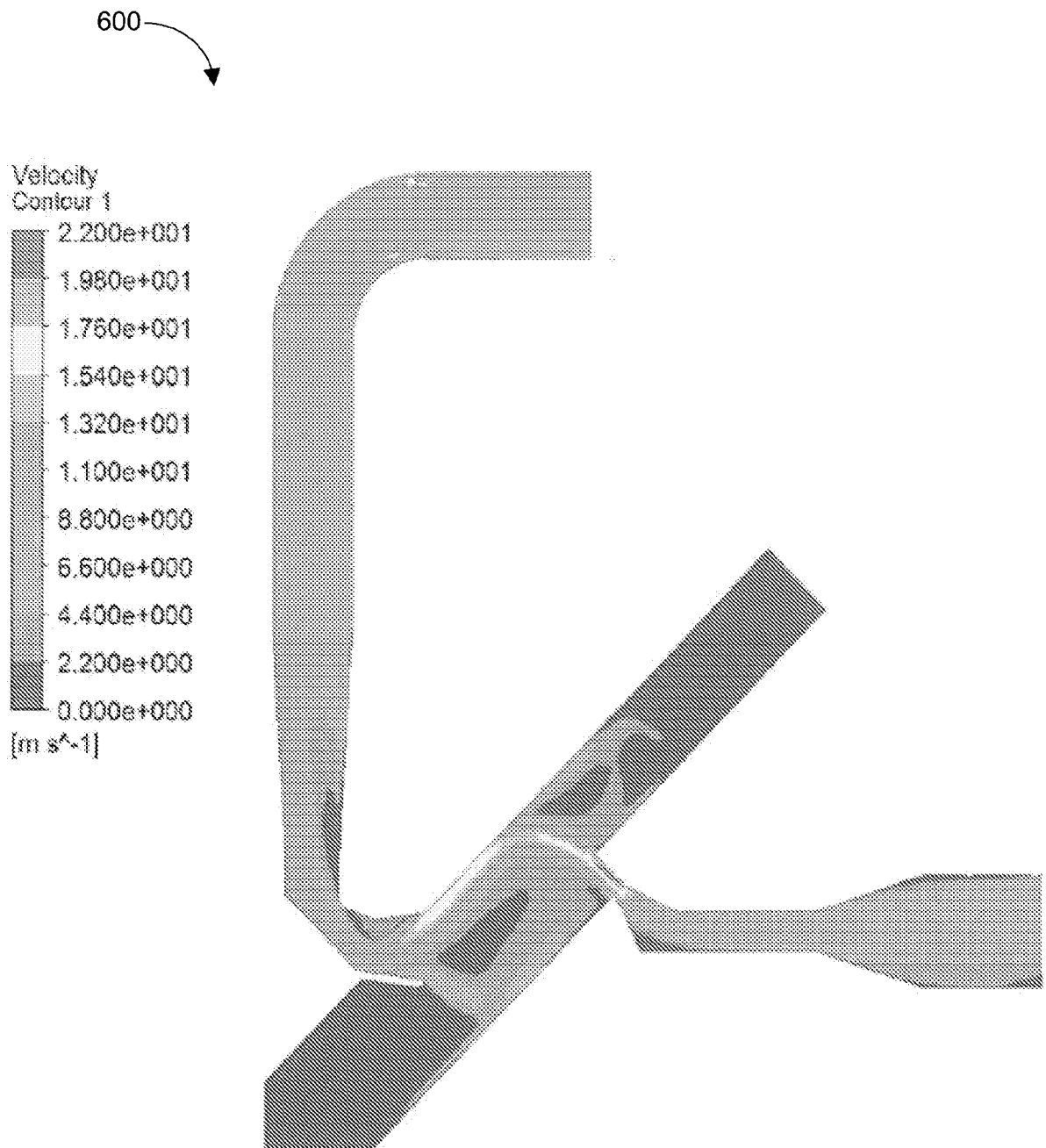


FIG. 6

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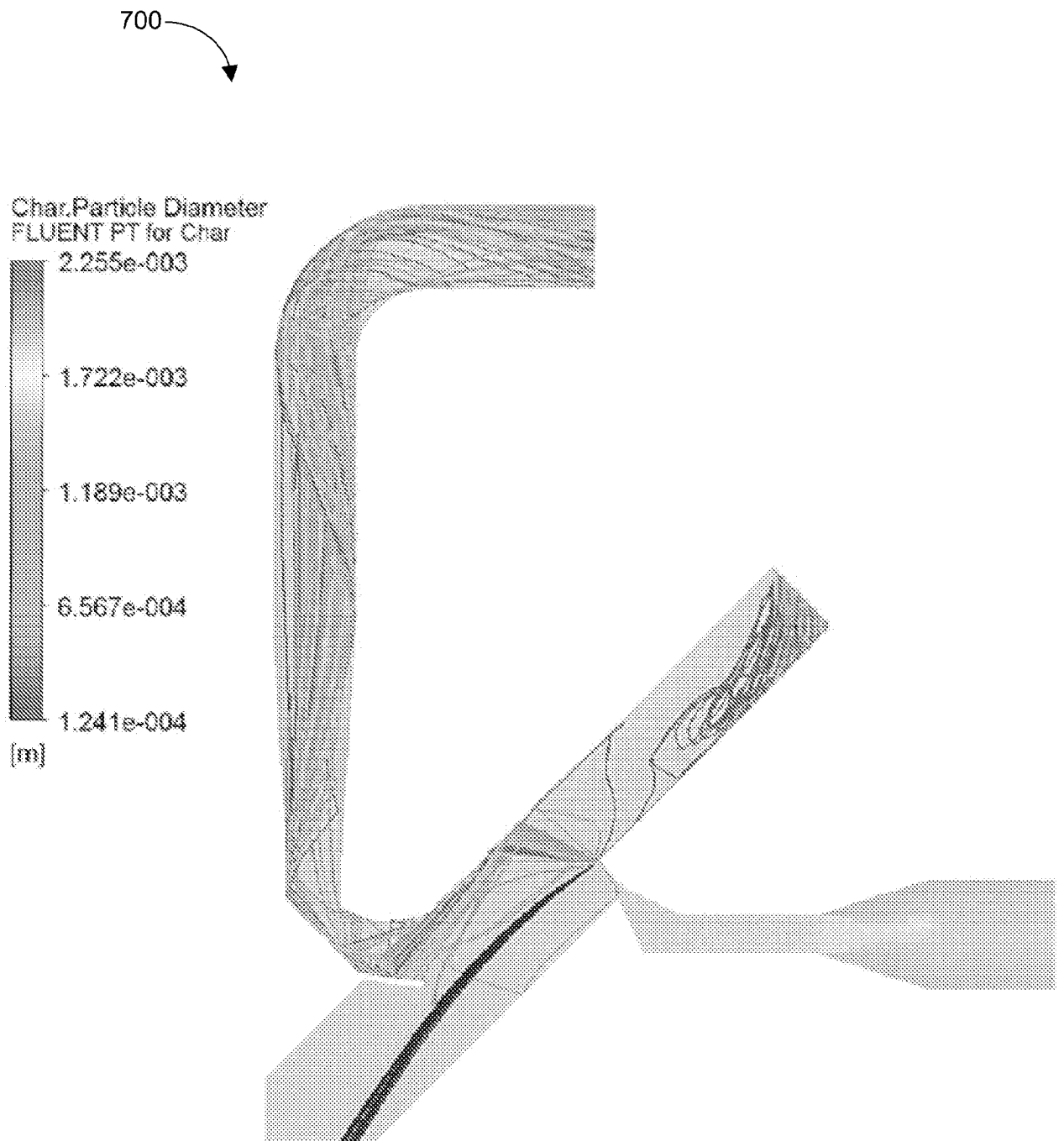


FIG. 7

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2014/042011

A. CLASSIFICATION OF SUBJECT MATTER
INV. B07B4/02 C10B53/00
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)

B07B 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)

EP0-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	GB 2 104 407 A (WORLD ENERGY RESOURCES CONSULTANCY LIMITED) 9 March 1983 (1983-03-09)	1-6, 10-18, 20-23, 26-32, 35, 37-46, 48, 51-75, 85-94
Y	the whole document	9,33,34, 36, 78-84, 95,96
A	----- -/--	8,76,77

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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Date of the actual completion of the international search

15 October 2014

Date of mailing of the international search report

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INTERNATIONAL SEARCH REPORT

International application No
PCT/US2014/042011

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	GB 367 482 A (THE CLEAN COAL COMPANY LIMITED ET AL) 25 February 1932 (1932-02-25)	1-8, 10-12, 37, 41-46, 48, 51-72, 76,77, 85,86
Y	page 2, line 100 - line 109	9,78-84
A	page 3, line 19 - line 47 page 4, line 38 - line 61 page 4, line 99 - page 5, line 23 claims	13-18, 31-35, 73-75, 93,95,96
Y	----- US 2012/228112 A1 (STEELE ET AL) 13 September 2012 (2012-09-13)	33,34, 36,95,96
A	abstract paragraph [0027] - paragraph [0037] claims figures	31,32, 35,93,94
X	----- DE 20 2006 014455 U1 (LHS CLEAN AIR SYSTEMS GMBH) 16 November 2006 (2006-11-16)	1-6, 10-12, 20-22, 24-30, 37-39, 41-46, 48, 50-72, 85-92
A	abstract paragraph [0016] - paragraph [0019] claims figures	14-16, 31,32, 35, 74-84, 93,96
X	----- WO 02/24348 A1 (ANDRITZ OY ET AL) 28 March 2002 (2002-03-28)	1-6, 10-14, 19, 37-39, 41-46, 48, 50-75, 85,86
A	abstract page 2, line 17 - page 4, line 6 claims figures	16-18, 24,25, 29-32, 35, 76-84, 93,96
	----- -/--	

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2014/042011

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 1 591 172 A1 (HAUNI PRIMARY GMBH) 2 November 2005 (2005-11-02)	1-6, 10-15, 20-22, 26-30, 37-39, 41-49, 51-69, 73-75, 85-92
A	abstract paragraph [0014] - paragraph [0015] paragraph [0018] claims figures	31,32, 35,93,96
X	----- US 4 314 899 A (STYRING JR) 9 February 1982 (1982-02-09) abstract column 2, line 13 - line 22 column 2, line 60 - column 3, line 4 column 3, line 29 - column 4, line 10 claims figures -----	1-6, 10-12, 31-35, 37, 40-46, 48, 51-72, 85,86, 93-96

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2014/042011

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
GB 2104407	A	09-03-1983	NONE
GB 367482	A	25-02-1932	NONE
US 2012228112	A1	13-09-2012	US 2012228112 A1 13-09-2012 WO 2012122351 A2 13-09-2012
DE 202006014455	U1	16-11-2006	DE 202006014455 U1 16-11-2006 EP 1900445 A1 19-03-2008
WO 0224348	A1	28-03-2002	AU 8996701 A 02-04-2002 FI 20002074 A 21-03-2002 WO 0224348 A1 28-03-2002
EP 1591172	A1	02-11-2005	AT 458558 T 15-03-2010 CN 1689715 A 02-11-2005 DE 102004020776 A1 24-11-2005 EP 1591172 A1 02-11-2005 JP 4707444 B2 22-06-2011 JP 2005312451 A 10-11-2005 US 2005236306 A1 27-10-2005
US 4314899	A	09-02-1982	NONE