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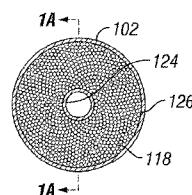
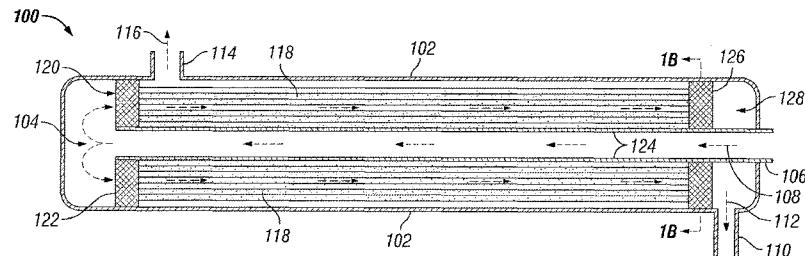
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(54) Title: COUNTER-FLOW GAS SEPARATION MODULES AND METHODS



(57) Abstract: A gas separation method includes flowing a gas feed along a feed flow path within a housing directionally from a product end to a feed end of a gas separation membrane. After the feed flow path, the gas feed flows along a membrane flow path defined by the membrane from the feed end to the product end. The feed flow path is counter to the membrane flow path. Heat may be exchanged between the feed flow path and the membrane flow path and increase separation efficiency. Also, heat exchanged may compensate for some temperature drop in the membrane due to enthalpy of gas separation. A gas separation module includes a feed flow path within a housing extending directionally from a product end to a feed end of a membrane. The feed flow path is counter to a membrane flow path defined by the membrane.

## Counter-Flow Gas Separation Modules and Methods

### TECHNICAL FIELD

Devices and methods herein pertain to gas separation modules, including

5 modules in aircraft fuel tank flammability reduction systems.

### BACKGROUND

Known air separation modules (ASMs) are found in aircraft fuel tank flammability reduction systems. The ASM removes some oxygen from air to generate nitrogen-10 enriched air (NEA), which then flows into fuel tank ullage, a region in the tank that often contains evaporated fuel (such as, fuel vapor). The NEA may reduce flammability of the fuel tank ullage. Federal Aviation Administration (FAA) regulations require that new and in-service transport aircraft include systems for enhancing the safety of aircraft fuel tanks. Unfortunately, ASMs add weight to aircraft. Accordingly, decreased weight of air 15 separation modules is desirable.

### SUMMARY

A gas separation method includes using a gas separation module including a housing and a gas separation membrane within the housing. The gas separation 20 membrane has a feed end and a product end with a retentate interior side and a permeate exterior side between the feed end and the product end. The method includes supplying a gas feed into the housing, the gas feed containing a first gas and different second gas. The gas feed flows along a feed flow path within the housing directionally

from the product end to the feed end of the gas separation membrane. The gas feed is segregated from contact with the permeate exterior side.

After the feed flow path, the gas feed flows along a membrane flow path defined by the gas separation membrane from the feed end to the product end of the gas

5 separation membrane. The feed flow path is counter to the membrane flow path. The method also includes contacting the retentate interior side with the gas feed in the membrane flow path, permeating at least some of the first gas from the gas feed through the gas separation membrane to the permeate exterior side, and producing retentate that is enriched in the second gas as a result of removing at least some of the

10 first gas from the gas feed.

By way of example, the method may include exchanging heat between the feed flow path and the membrane flow path as enabled by the feed flow path being counter to the membrane flow path and, as a result, increasing a separation efficiency of the gas separation module. The method may further include providing a configuration for the

15 gas separation module, selecting one or more process conditions, and, as a result, compensating for at least a portion of a temperature drop in the gas separation membrane due to enthalpy of gas separation. A temperature of the product end of the gas separation membrane may be established within 10° F of a temperature of the feed end of the gas separation membrane.

20 A gas separation module includes a housing having a feed port enabling inlet of gas feed, a permeate port enabling outlet of permeate, and a retentate port enabling outlet of retentate. The module includes a gas separation membrane within the housing, the gas separation membrane having a feed end and a product end with a retentate interior side and a permeate exterior side between the feed end and the product end. A

feed flow path is within the housing and extends directionally from the product end to the feed end of the gas separation membrane and is segregated from contact with the permeate exterior side. The feed flow path is counter to a membrane flow path defined by the gas separation membrane and extending from the feed end to the product end of

5 the gas separation membrane enabling contact with the retentate interior side.

The features, functions, and advantages that have been discussed can be achieved independently in various embodiments or may be combined in yet other embodiments further details of which can be seen with reference to the following description and drawings.

10

#### BRIEF DESCRIPTION OF THE DRAWINGS

Some devices and methods are described below with reference to the following accompanying drawings.

15 Figs. 1A-4C are cross-sectional views of counter-feed gas separation modules according to several configurations.

Figs. 5 and 6 are isometric and close-up views, respectively, of a prior art gas separation module.

Fig. 7 shows a fuel tank flammability reduction system.

20 DETAILED DESCRIPTION

Some known gas separation modules use hollow fiber membranes (HFM). HFM may include a fiber wall of a permeable, porous material supporting a thin membrane or skin thereon of a different material providing selectivity in the gas separation process. Such HFM are referred to as composite membranes given the

different materials included. HFM<sup>s</sup> that are not composite may include a skin using the same material as the porous support and may be referred to as asymmetric membranes, given the varying transport properties across the HFM thickness. Although a focus on hollow fiber membranes exists for gas separation processes, other types of

5 gas separation membranes might be used in the devices and methods herein.

During operation of the gas separation module, gas feed enters a feed end of the fibers and selected gasses diffuse through fiber walls to produce permeate. Retained gasses proceed down the hollow fibers to the product end and exit as retentate. Both ends of the hollow fiber membranes may be potted with resin to secure the fibers. The

10 potted resin securing the fiber ends forms tubesheets at each end that segregate the gas feed and the retentate from the permeate. The combination of the fibers and tubesheets forms an element that may be inserted in a shell to form the module. Some may be refer to the element as a “cartridge” and to the shell as a “canister.” However, in the present document, the meaning of “element” and “shell” are not limited to the

15 respective ordinary meanings of “cartridge” and “canister.” Generally, the potted resin forms a plug with a circular perimeter around the respective fiber ends fitted within a tube-shaped shell. Even so, the configurations herein include additional geometries for tubesheets and shells.

For some applications in which a gas separation module is used, such as a fuel

20 tank flammability reduction system, gas feed may be supplied at an elevated temperature. For separation of oxygen from air, and for other gas pairs, separation efficiency may increase with increased temperature of gas feed. Beneficially, a readily available gas source might supply heated gas as a byproduct of an unrelated process.

In aircraft, engine bleed air is a known source for gas feed to an air separation module and often reaches the air separation module at 160° F to 300° F

Figures 5 and 6 show a known gas separation module 500 including a shell 502 in which element 520 is installed. A feed port 506 allows entry of a gas feed 508 to 5 contact tubesheet 522 and enter fibers 518 assembled around a support 524. A rim 504 around tubesheet 522 is provided to seal tubesheet 522 within shell 502. Consequently, gas feed 508 flows into an individual fiber 518 (shown in Figure 6) to produce permeate 516, which passes through the wall of individual fiber 518. Retentate 512 exits individual fiber 518 at another tubesheet (not shown in Figure 5) and flows through a retentate 10 port 510. Permeate 516 from each of fibers 518 collects between tubesheet 522 and the other tubesheet and flows through permeate port 514.

The temperature along fibers 518 in the known flow-through design shown in Figures 5 and 6 decreases as gas feed 508 flows downstream from tubesheet 522 to the other tubesheet (not shown). The temperature profile may depend on the flow rate 15 of gas feed 508 and may drop up to 50 °F, or even 70 °F, from tubesheet 522 to the other tubesheet. The cooling may be partly due to the enthalpy of separation of gases associated with one gas permeating preferentially through the membranes of fibers 518 to produce permeate 516 and retentate 512. Also, the cooling may be partly due to a pressure drop as gas feed 508 flows down the length of fibers 518. Because the 20 efficiency of gas separation through a membrane decreases with decreasing temperature, the decreasing temperature profile along fibers 518 likewise reduces separation efficiency along fibers 518, yielding a related decreasing profile for separation efficiency.

Expected separation efficiency represents one factor in sizing a gas separation module. As the separation efficiency decreases, module size, and thus module weight, may increase to provide a suitable amount of retentate flow despite a decreased efficiency. Consequently, an opportunity to decrease gas separation module weight

5 exists in increasing separation efficiency. The amount of retentate produced by a gas separation module may be increased by establishing a temperature profile along fibers 518 that does not drop as significantly as described above. The overall separation efficiency of a gas separation module may increase when the temperature drop is reduced; that is, if temperature at the other tubesheet (not shown) downstream

10 increases to a temperature closer to that at tubesheet 522.

One possibility for increasing gas separation efficiency includes exchanging heat between gas feed and a gas separation membrane. A gas separation method includes using a gas separation module including a housing and a gas separation membrane within the housing. The gas separation membrane has a feed end and a product end

15 with a retentate interior side and a permeate exterior side between the feed end and the product end. The method includes supplying a gas feed into the housing, the gas feed containing a first gas and different second gas. The gas feed flows along a feed flow path within the housing directionally from the product end to the feed end of the gas separation membrane. The gas feed is segregated from contact with the permeate

20 exterior side.

After the feed flow path, the gas feed flows along a membrane flow path defined by the gas separation membrane from the feed end to the product end of the gas separation membrane. The feed flow path is counter to the membrane flow path. The method also includes contacting the retentate interior side with the gas feed in the

membrane flow path, permeating at least some of the first gas from the gas feed through the gas separation membrane to the permeate exterior side, and producing retentate that is enriched in the second gas as a result of removing at least some of the first gas from the gas feed.

5 By way of example, the gas separation module may be an air separation module included in an aircraft fuel tank flammability reduction system. The gas feed is then an air feed, the first gas is oxygen, and the second gas is nitrogen. Consequently, the method may further include supplying the retentate, which contains nitrogen-enriched air, to a fuel tank on board the aircraft.

10 The method may further include exchanging heat between the feed flow path and the membrane flow path as enabled by the feed flow path being counter to the membrane flow path. The concept and benefits of counter-current heat transfer between a hot fluid and a cold fluid to increase heat exchange efficiency is known in the context of counter-current heat exchangers. However, in counter-current heat exchangers, such 15 as shell-and-tube heat exchangers, a hot fluid contacts a tube containing a different cold fluid to heat the cold fluid.

In contrast, the present method includes a hot fluid (gas feed) heating a downstream flow of the same fluid inside the gas separation module to counteract internal cooling caused by processing inside the module. Also, in contrast, the gas feed 20 is segregated from contact with the permeate exterior side of the gas separation membrane. Accordingly, the hot fluid (gas feed) does not contact the tube (gas separation membrane) containing the cold fluid.

The method may include establishing a temperature of the product end of the gas separation membrane that is within 10° F of a temperature of the feed end of the

gas separation membrane. As flow rate increases, the product end temperature may increase to more closely approach the feed end temperature. Consequently, the method may include providing a configuration for the gas separation module, selecting one or more process conditions (such as flow rate), and, as a result, compensating for at least 5 a portion of a temperature drop in the gas separation membrane due to enthalpy of gas separation.

Using the feed flow path counter to the membrane flow path may raise the product end temperature for a wide range of gas feed flow rate. At lower flow rates, though product end temperature may increase, the temperature profile along the 10 membrane may be less uniform in comparison to the temperature profile at higher flow rates. Lower flow rates may allow more drop in temperature between the feed end and the product end followed by a temperature rise at the product end. Higher flow rates may allow less drop in temperature between the feed end and the product end, increasing temperature uniformity. Since the increased temperature may be established 15 along more of the membrane, separation efficiency may further increase at higher flow rates.

The housing may include an inner shell and an outer shell, the gas separation membrane may be within the inner shell, and flowing the gas feed along the feed flow path may include flowing the gas feed along a passage between the inner shell and the 20 outer shell. Flowing the gas feed along the feed flow path or flowing the gas feed along the membrane flow path or both may include flowing the gas feed along a plurality of separated flow paths.

The gas separation membrane may include a plurality of hollow fiber membranes; the gas separation module may include a feed tubesheet within the

housing securing the feed end of the fibers and a product tubesheet within the housing securing the product end of the fibers. As a result, the method may further include segregating the gas feed and the permeate exterior side of the fibers with the feed tubesheet and segregating the permeate exterior side of the fibers and the retentate 5 with the product tubesheet. Additionally, the feed flow path may extend among the fibers and the method may further include segregating the feed flow path from contact with the permeate exterior side.

Figures 1A and 1B show a gas separation module 100 that may be used to implement the methods described herein. Gas separation module 100 includes a shell 10 102 having a feed port 106 that enables inlet of a gas feed 108. Gas feed 108 flows through a support 124 that extends from a product tubesheet 126 to a feed tubesheet 122. Gas feed 108 flows into a header 104 associated with feed tubesheet 122. Gas feed 108 then flows into the feed end of fibers 118 at feed tubesheet 122. Gas separation module 100 thus provides a feed flow path among fibers 118, but is 15 segregated from a permeate side of fibers 118 by support 124.

Fibers 118 and tubesheets 122 and 126 in combination form an element 120 within shell 102. Selected gases of gas feed 108 flow through element 120 via fibers 118 and permeate through fibers 118 to produce a permeate 116. Permeate 116 collects between feed tubesheet 122 and product tubesheet 126 and exits through 20 permeate port 114. Gases remaining in fibers 118 flow out the product end of fibers 118 at product tubesheet 126 and into a header 128 to provide a retentate 112, which exits through a retentate port 110.

It will be appreciated that gas separation module 100 also provides a membrane flow path defined by fibers 118 and extending from the feed end to the product end of

such fibers. Consequently, Figure 1A shows a feed flow path that is counter to a membrane flow path. The counter feed arrangement of gas flow through gas separation module 100 enables heat exchange between the feed flow path and the membrane flow path. As a result, a temperature of the product end of fibers 118 may increase to a 5 temperature that is closer to a temperature of the feed end of fibers 118. A temperature drop along fibers 118 may be reduced compared to a temperature drop in the known flow-through design shown in Figures 5 and 6. The overall separation efficiency of gas separation module 100 may increase when the temperature drop is reduced. Also, a temperature profile within element 120 may have increased uniformity, depending on 10 gas feed 108 flow rate, and further increase separation efficiency.

Figures 2A and 2B show a gas separation module 200 that may also be used to implement the methods described herein. Gas separation module 200 includes a shell 232 having a feed port 206 that enables inlet of a gas feed 208. Gas feed 208 flows around a shell 202 within shell 232 and flows into a passage 230 between shell 232 and 15 shell 202. Spacers 236 (Figure 2B) support shell 202 within shell 232 and may extend the length of shell 202 or some portion thereof. After flowing down passage 230, gas feed 208 flows into a header 204 associated with a feed tubesheet 222. Gas feed 208 then flows into the feed end of fibers 218 at feed tubesheet 222.

A support 224 is provided in an element 220 that includes feed tubesheet 222, a 20 product tubesheet 226, and fibers 218 extending there between. Gas separation module 200 thus provides a feed flow path that is segregated from a permeate side of fibers 218 by shell 202. Although support 224 is hollow, plugs 234 are inserted at feed tubesheet 222 and product tubesheet 226 to keep gas from flowing through support 224. The hollow nature of support 224 may reduce the weight of gas separation module 200.

Selected gases of gas feed 208 flow through element 220 via fibers 218 and permeate through fibers 218 to produce a permeate 216. Permeate 216 collects between feed tubesheet 222 and product tubesheet 226 and exits through permeate port 214. Gases remaining in fibers 218 flow out the product end of fibers 218 at product 5 tubesheet 226 and collect in a header 228 to provide a retentate 212, which exits through a retentate port 210. It will be appreciated that gas separation module 200 also provides a membrane flow path defined by fibers 218 and extending from the feed end to the product end of such fibers. Consequently, Figure 2A shows a feed flow path that is counter to a membrane flow path. The counter feed arrangement enables heat 10 exchange between the feed flow path and the membrane flow path.

As a result, a temperature of the product end of fibers 218 may increase to a temperature that is closer to a temperature of the feed end of fibers 218. A temperature drop along fibers 218 may be reduced compared to a temperature drop in the known flow-through design shown in Figures 5 and 6. The overall separation efficiency of gas 15 separation module 200 may increase when the temperature drop is reduced. Also, a temperature profile within element 220 may have increased uniformity, depending on gas feed 208 flow rate, and further increase separation efficiency.

Figures 3A and 3B show a gas separation module 300 that combines the features of gas separation modules 100 and 200. Gas separation module 300 in Figures 20 3A and 3B may also be used to implement the methods described herein. Gas separation module 300 includes a shell 332 having a feed port 306a that enables inlet of a gas feed 308. Gas feed 308 flows around a shell 302 within shell 332 and into a passage 330 between shell 332 and shell 302. Spacers 336 (Figure 3B) support shell 302 within shell 332 and may extend the length of shell 302 or some portion thereof.

After flowing down passage 330, gas feed 308 flows into a header 304 associated with a feed tubesheet 322. Gas feed 308 then flows into the feed end of fibers 318 at feed tubesheet 322. Gas separation module 300 also includes a feed port 306b that enables inlet of gas feed 308 into a support 324, which extends from a product tubesheet 326 to 5 feed tubesheet 322. Support 324 also connects with feed port 306b or integrally includes feed port 306b to receive gas feed 308, which flows into header 304.

An element 320 includes feed tubesheet 322, product tubesheet 326, support 324, and fibers 318. Gas separation module 300 thus provides a feed flow path that is segregated from a permeate side of fibers 318 by shell 302. Gas separation module 300 10 also provides a feed flow path among fibers 318 that is segregated from the permeate side of fibers 318 by support 324.

Selected gases of gas feed 308 flow through element 320 via fibers 318 and permeate through fibers 318 to produce a permeate 316. Permeate 316 collects between feed tubesheet 322 and product tubesheet 326 and exits through permeate 15 port 314. Gases remaining in fibers 318 flow out the product end of fibers 318 at product tubesheet 326 and collect in a header 328 to provide a retentate 312, which exits through a retentate port 310. It will be appreciated that gas separation module 300 also provides a membrane flow path defined by fibers 318 and extending from the feed end to the product end of such fibers. Consequently, Figure 3A shows a feed flow path that 20 is counter to a membrane flow path. The counter feed arrangement enables heat exchange between the feed flow path and the membrane flow path.

As a result, the product end of fibers 318 may increase to a temperature that is closer to a temperature of the feed end of fibers 318. A temperature drop along fibers 318 may be reduced compared to a temperature drop in the known flow-through design

shown in Figures 5 and 6. The overall separation efficiency of gas separation module 300 may increase when the temperature drop is reduced. Also, a temperature profile within element 320 may have increased uniformity, depending on gas feed 308 flow rate, and further increase separation efficiency.

5 Figures 4A, 4B, and 4C show a gas separation module 400 that may be used to implement the methods described herein. Gas separation module 400 includes a shell 402 having a feed port 406 that enables inlet of a gas feed 408 into a header 438 between shell 402 and an interior wall 436. Gas feed 408 flows through a support 424 that extends from a product tubesheet 426 to a feed tubesheet 422. Support 424 also 10 extends through wall 436 to receive gas feed 408, which flows from header 438 into a header 404 associated with feed tubesheet 422. Gas feed 408 then flows into the feed end of fibers 418 at feed tubesheet 422. Gas separation module 400 thus provides a feed flow path among fibers 418, but is segregated from a permeate side of fibers 418 by support 424.

15 In addition to support 424, gas separation module 400 further includes conduits 444. Gas feed 408 flows through conduits 444 that extend from product tubesheet 426 to feed tubesheet 422. Conduits 444 also extend through wall 436 to receive gas feed 408, which flows from header 438 into header 404. Gas feed 408 then flows into the feed end of fibers 418. Gas separation module 400 thus provides an additional feed flow 20 path among fibers 418, but is segregated from a permeate side of fibers 418 by conduit 444.

Fibers 418 and tubesheets 422 and 426 in combination form an element 420 within shell 402. Selected gases of gas feed 408 flow through element 420 via fibers 418 and permeate through fibers 418 to produce a permeate 416. Permeate 416

collects between feed tubesheet 422 and product tubesheet 426 and exits through permeate port 414. Gases remaining in fibers 418 flow out the product end of fibers 418 at product tubesheet 426 and into a header 428 between product tubesheet 426 and wall 436 to provide a retentate 412, which exits through a retentate port 410.

5 It will be appreciated that gas separation module 400 also provides a membrane flow path defined by fibers 418 and extending from the feed end to the product end of such fibers. Consequently, Figures 4A and 4B show a feed flow path that is counter to a membrane flow path. The counter feed arrangement of gas flow through gas separation module 400 enables heat exchange between the feed flow path and the membrane flow 10 path. As a result, the product end of fibers 418 may increase to a temperature that is closer to a temperature of the feed end of fibers 418. A temperature drop along fibers 418 may be reduced compared to a temperature drop in the known flow-through design shown in Figures 5 and 6. The overall separation efficiency of gas separation module 400 may increase when the temperature drop is reduced. Also, a temperature profile 15 within element 420 may have increased uniformity, depending on gas feed 408 flow rate, and further increase separation efficiency.

Conduits 444 are in a V-shape, but other geometries are conceivable. Each of the four conduits 444 shown in Figure 4C may have an arc length at the periphery of product tubesheet 426 that encompasses about 2% of the tubesheet circumference, for 20 a total of 8% of the circumference. Conduits 444 may extend from more than one-half to about two-thirds of the radius of tubesheets 422 and 426 to allow for heat transfer area. By spacing conduits 444 around support 424, heat from gas feed 408 may be distributed more efficiently among fibers 418. A design for a gas separation module may account for the loss of flow through element 420 due to replacing some of fibers 418

with conduits 444. Flow loss may be balanced against the gain in retentate production from increased separation efficiency due to a temperature increase at the product end of fibers 418.

Known techniques for forming a gas separation module may include winding a fiber material onto the support. Known techniques for winding fiber material onto a support, including spiral and diagonal winding, may be used with accommodation for any conduits by also winding fiber material onto the conduits or leaving a space where conduits may be inserted. As an alternative for straight winding, not diagonal or spiral, slots may be machined into feed and product tubesheets and conduits inserted in the slots among the fibers. Although fiber material is often wound onto supports, known module designs exist that do not include a support. Nevertheless, conduits may be inserted later by machining a space in tubesheets or leaving a space using other techniques.

Supports 124, 324, and 424, conduits 444, and passages 230 and 330 that provide feed flow paths are shown as hollow in the Figures. However, they may instead be partially or fully filled with porous material that allows gas flow through the porous material. The porous material may provide structural support to the supports, conduits, and passages. Low density, open cell, metal foams may be used. An example of low density foam includes foam having a density of less than 15 pounds per cubic foot (lb/ft<sup>3</sup>), such as 8-15 lb/ft<sup>3</sup>. An example of metal foam includes aluminum foam. A metallic honeycomb may be used as the porous material and provide structural support as well as enhanced heat transfer with minimal pressure loss. The metallic honeycomb may have a density of 3-6 lb/ft<sup>3</sup>.

It will be appreciated that yet further gas separation modules may be used to implement the methods described herein. Even though gas separation modules 100, 200, 300, and 400 in the Figures have a circular cross-section, other geometries for the respective shells and elements are conceivable. Accordingly, a gas separation module

5 includes a housing having a feed port enabling inlet of gas feed, a permeate port enabling outlet of permeate, and a retentate port enabling outlet of retentate. The module includes a gas separation membrane within the housing, the gas separation membrane having a feed end and a product end with a retentate interior side and a permeate exterior side between the feed end and the product end. A feed flow path is

10 within the housing and extends directionally from the product end to the feed end of the gas separation membrane and is segregated from contact with the permeate exterior side. The feed flow path is counter to a membrane flow path defined by the gas separation membrane and extending from the feed end to the product end of the gas separation membrane enabling contact with the retentate interior side.

15 By way of example, the feed flow path counter to the membrane flow path may enable heat exchange between the feed flow path and the membrane flow path. The gas separation module may be an air separation module comprised by an aircraft fuel tank flammability reduction system. The system may include a source for air to the feed port and a fuel tank on board the aircraft to receive the retentate, which contains

20 nitrogen-enriched air.

The housing may include at least one additional port selected from the group consisting of an additional feed port, an additional permeate port, and an additional retentate port. The housing may include an inner shell and an outer shell, the gas separation membrane being within the inner shell, and a passage between the inner

shell and the outer shell defining at least part of the feed flow path. The passage may have a first end in fluid communication with the feed port and a second end in fluid communication with the feed end of the gas separation membrane, the inner shell segregating the feed flow path from contact with the permeate exterior side of the gas

5 separation membrane.

The feed flow path or the membrane flow path or both may include a plurality of separated flow paths. The feed flow path may be defined in part by at least one support for the gas separation membrane, the at least one support being selected from the group consisting of a hollow support and a porous support.

10 The gas separation membrane may include a plurality of hollow fiber membranes. The gas separation module may further include a feed tubesheet within the housing securing the feed end of the fibers and enabling segregation of the gas feed and the permeate exterior side of the fibers. The gas separation module may still further include a product tubesheet within the housing securing the product end of the fibers

15 and enabling segregation of the permeate exterior side of the fibers and the retentate. The feed flow path may extend among the fibers, but be segregated from contact with the permeate exterior side. The feed flow path may be defined in part by a conduit extending among the fibers, having a first end secured by the product tubesheet, and having a second end secured by the feed tubesheet. The first end may be in fluid

20 communication with the feed port, the conduit segregating the feed flow path from contact with the permeate exterior side of the fibers, and the second end may be in fluid communication with the feed end of the fibers. The conduit may include a plurality of separated conduits.

Figure 7 shows a system 700 with an ASM 702 that may include the gas separation modules described herein. An air source 706 may be pressurized, as shown in Figure 7, or at ambient pressure. Even so, separation efficiency often increases with increasing pressure, as in the case of hollow fiber membrane production of nitrogen-enriched air. Air source 706 provides air feed 710 to ASM 702, which produces permeate 708 and nitrogen-enriched air 712. A fuel tank 704 enables receipt of nitrogen-enriched air 712 to reduce flammability of fuel tank ullage. ASM 702 may offer the benefits of the methods and devices described herein.

Further, the disclosure comprises embodiments according to the following 10 clauses:

1. A gas separation module comprising:
  - a housing having a feed port enabling inlet of gas feed, a permeate port enabling outlet of permeate, and a retentate port enabling outlet of retentate;
  - a gas separation membrane within the housing, the gas separation membrane having a feed end and a product end with a retentate interior side and a permeate exterior side between the feed end and the product end; and
  - a feed flow path within the housing and extending directionally from the product end to the feed end of the gas separation membrane and being segregated from contact with the permeate exterior side, the feed flow path being counter to a membrane flow path defined by the gas separation membrane and extending from the feed end to the product end of the gas separation membrane enabling contact with the retentate interior side.

2. The module of clause 1 wherein the feed flow path counter to the membrane flow path enables heat exchange between the feed flow path and the membrane flow path.

3. The module of clause 1 wherein the gas separation module is an air separation module comprised by an aircraft fuel tank flammability reduction system, the system further comprising:

a source for air to the feed port; and  
a fuel tank on board the aircraft to receive the retentate, which contains nitrogen-enriched air.

10 4. The module of clause 1 wherein the housing comprises at least one additional port selected from the group consisting of an additional feed port, an additional permeate port, and an additional retentate port.

5. The module of clause 1 wherein the housing comprises an inner shell and an outer shell, the gas separation membrane is within the inner shell, and a passage 15 between the inner shell and the outer shell defines at least part of the feed flow path.

6. The module of clause 5 wherein the passage has a first end in fluid communication with the feed port and a second end in fluid communication with the feed end of the gas separation membrane, the inner shell segregating the feed flow path from contact with the permeate exterior side of the gas separation membrane.

20 7. The module of clause 1 wherein the feed flow path or the membrane flow path or both comprise a plurality of separated flow paths.

8. The module of clause 1 wherein the feed flow path is defined in part by at least one support for the gas separation membrane, the at least one support being selected from the group consisting of a hollow support and a porous support.

9. The module of clause 1 wherein the gas separation membrane comprises

5 a plurality of hollow fiber membranes and the gas separation module further comprises:

a feed tubesheet within the housing securing the feed end of the plurality of hollow fiber membranes and enabling segregation of the gas feed and the permeate exterior side of the plurality of hollow fiber membranes; and

10 a product tubesheet within the housing securing the product end of the plurality of hollow fiber membranes and enabling segregation of the permeate exterior side of the plurality of hollow fiber membranes and the retentate.

10. The module of clause 8 wherein the feed flow path extends among the plurality of hollow fiber membranes, but is segregated from contact with the permeate exterior side.

15 11. The module of clause **Error! Reference source not found.** wherein the feed flow path is defined in part by a conduit extending among the plurality of hollow fiber membranes, having a first end secured by the product tubesheet, and having a second end secured by the feed tubesheet, the first end being in fluid communication with the feed port, the conduit segregating the feed flow path from contact with the 20 permeate exterior side of the plurality of hollow fiber membranes, and the second end being in fluid communication with the feed end of the plurality of hollow fiber membranes.

12. A gas separation method comprising:
  - using a gas separation module including a housing and a gas separation membrane within the housing, the gas separation membrane having a feed end and a product end with a retentate interior side and a permeate exterior side between the feed end and the product end;
  - 5 supplying a gas feed into the housing, the gas feed containing a first gas and a different second gas;
  - flowing the gas feed along a feed flow path within the housing directionally from the product end to the feed end of the gas separation membrane, the gas feed being segregated from contact with the permeate exterior side;
  - 10 after the feed flow path, flowing the gas feed along a membrane flow path defined by the gas separation membrane from the feed end to the product end of the gas separation membrane, the feed flow path being counter to the membrane flow path; and
  - 15 contacting the retentate interior side with the gas feed in the membrane flow path, permeating at least some of the first gas from the gas feed through the gas separation membrane to the permeate exterior side, and producing retentate that is enriched in the second gas as a result of removing at least some of the first gas from the gas feed.

13. The method of clause 9 wherein the gas separation module is an air separation module comprised by an aircraft fuel tank flammability reduction system, the gas feed comprises an air feed, the first gas comprises oxygen, the second gas comprises nitrogen and the method further comprises:

5 supplying the retentate, which contains nitrogen-enriched air, to a fuel tank on board the aircraft.

14. The method of clause 9 further comprising exchanging heat between the feed flow path and the membrane flow path as enabled by the feed flow path being counter to the membrane flow path and, as a result, increasing a separation efficiency  
10 of the gas separation module.

15. The method of clause 9 further comprising establishing a temperature of the product end of the gas separation membrane that is within 10° F of a temperature of the feed end of the gas separation membrane.

16. The method of clause 9 further comprising providing a configuration for  
15 the gas separation module, selecting one or more process conditions, and, as a result, compensating for at least a portion of a temperature drop in the gas separation membrane due to enthalpy of gas separation.

17. The method of clause 9 wherein the housing comprises an inner shell and an outer shell, the gas separation membrane is within the inner shell, and flowing the  
20 gas feed along the feed flow path comprises flowing the gas feed along a passage between the inner shell and the outer shell.

18. The method of clause 9 wherein flowing the gas feed along the feed flow path or flowing the gas feed along the membrane flow path or both comprise flowing the gas feed along a plurality of separated flow paths.

19. The method of clause 9 wherein the gas separation membrane comprises

5 a plurality of hollow fiber membranes, the gas separation module comprises a feed tubesheet within the housing securing the feed end of the plurality of hollow fiber membranes and a product tubesheet within the housing securing the product end of the plurality of hollow fiber membranes, and the method further comprises:

10 segregating the gas feed and the permeate exterior side of the plurality of hollow fiber membranes with the feed tubesheet; and

segregating the permeate exterior side of the plurality of hollow fiber membranes and the retentate with the product tubesheet.

20. The method of clause 15 wherein the feed flow path extends among the

plurality of hollow fiber membranes and the method further comprises segregating the

15 feed flow path from contact with the permeate exterior side.

In compliance with the statute, the devices and methods have been described in language more or less specific as to structural and methodical features. It is to be understood, however, that the devices and methods are not limited to the specific features shown and described. The devices and methods are, therefore, claimed in any 20 of their forms or modifications within the proper scope of the appended claims appropriately interpreted in accordance with the doctrine of equivalents.

TABLE OF REFERENCE NUMERALS FOR FIGURES

100 module	300 module	500 module
102 shell	302 shell	502 shell
104 header	304 header	504 rim
106 feed port	306a feed port	506 feed port
108 feed	306b feed port	508 feed
110 retentate port	308 feed	510 retentate port
112 retentate	310 retentate port	512 retentate
114 permeate port	312 retentate	514 permeate port
116 permeate	314 permeate port	516 permeate
118 fiber(s)	316 permeate	518 fiber(s)
120 element	318 fiber(s)	520 element
122 feed tubesheet	320 element	522 feed tubesheet
124 support	322 feed tubesheet	524 support
126 product	324 support	
tubesheet	326 product	700 system
128 header	tubesheet	702 ASM
	328 header	704 fuel tank
200 module	330 passage	706 air source
202 shell	332 shell	708 permeate
204 header	336 spacer	710 air feed
206 feed port		712 nitrogen-enriched air
208 feed	400 module	
210 retentate port	402 shell	
212 retentate	404 header	
214 permeate port	406 feed port	
216 permeate	408 feed	
218 fiber(s)	410 retentate port	
220 element	412 retentate	
222 feed tubesheet	414 permeate port	
224 support	416 permeate	
226 product	418 fiber(s)	
tubesheet	420 element	
228 header	422 feed tubesheet	
230 passage	424 support	
232 shell	426 product	
234 plug	tubesheet	
236 spacer	428 header	
	436 wall	
	438 header	
	444 conduit	

## CLAIMS

What is claimed is:

1. A gas separation module comprising:
  - a housing having a feed port enabling inlet of gas feed, a permeate port enabling outlet of permeate, and a retentate port enabling outlet of retentate;
  - a gas separation membrane within the housing, the gas separation membrane having a feed end and a product end with a retentate interior side and a permeate exterior side between the feed end and the product end; and
  - a feed flow path within the housing and extending directionally from the product end to the feed end of the gas separation membrane and being segregated from contact with the permeate exterior side, the feed flow path being counter to a membrane flow path defined by the gas separation membrane and extending from the feed end to the product end of the gas separation membrane enabling contact with the retentate interior side.
2. The module of claim 1 wherein the feed flow path counter to the membrane flow path enables heat exchange between the feed flow path and the membrane flow path.

3. The module of any preceding claim wherein the gas separation module is an air separation module comprised by an aircraft fuel tank flammability reduction system, the system further comprising:

a source for air to the feed port; and  
a fuel tank on board the aircraft to receive the retentate, which contains nitrogen-enriched air.

4. The module of any preceding claim wherein the housing comprises at least one additional port selected from the group consisting of an additional feed port, an additional permeate port, and an additional retentate port.

5. The module of any preceding claim wherein the housing comprises an inner shell and an outer shell, the gas separation membrane is within the inner shell, and a passage between the inner shell and the outer shell defines at least part of the feed flow path, and wherein the passage has a first end in fluid communication with the feed port and a second end in fluid communication with the feed end of the gas separation membrane, the inner shell segregating the feed flow path from contact with the permeate exterior side of the gas separation membrane.

6. The module of any preceding claim wherein the feed flow path or the membrane flow path or both comprise a plurality of separated flow paths.

7. The module of any preceding claim wherein the feed flow path is defined in part by at least one support for the gas separation membrane, the at least one support being selected from the group consisting of a hollow support and a porous support.

8. The module of any preceding claim wherein the gas separation membrane comprises a plurality of hollow fiber membranes and the gas separation module further comprises:

a feed tubesheet within the housing securing the feed end of the plurality of hollow fiber membranes and enabling segregation of the gas feed and the permeate exterior side of the plurality of hollow fiber membranes; and

a product tubesheet within the housing securing the product end of the plurality of hollow fiber membranes and enabling segregation of the permeate exterior side of the plurality of hollow fiber membranes and the retentate, wherein the feed flow path extends among the plurality of hollow fiber membranes, but is segregated from contact with the permeate exterior side, and wherein the feed flow path is defined in part by a conduit extending among the plurality of hollow fiber membranes, having a first end secured by the product tubesheet, and having a second end secured by the feed tubesheet, the first end being in fluid communication with the feed port, the conduit segregating the feed flow path from contact with the permeate exterior side of the plurality of hollow fiber membranes, and the second end being in fluid communication with the feed end of the plurality of hollow fiber membranes.

9. A gas separation method comprising:

using a gas separation module including a housing and a gas separation membrane within the housing, the gas separation membrane having a feed end and a product end with a retentate interior side and a permeate exterior side between the feed end and the product end;

supplying a gas feed into the housing, the gas feed containing a first gas and a different second gas;

flowing the gas feed along a feed flow path within the housing directionally from the product end to the feed end of the gas separation membrane, the gas feed being segregated from contact with the permeate exterior side;

after the feed flow path, flowing the gas feed along a membrane flow path defined by the gas separation membrane from the feed end to the product end of the gas separation membrane, the feed flow path being counter to the membrane flow path; and

contacting the retentate interior side with the gas feed in the membrane flow path, permeating at least some of the first gas from the gas feed through the gas separation membrane to the permeate exterior side, and producing retentate that is enriched in the second gas as a result of removing at least some of the first gas from the gas feed.

10. The method of claim 9 wherein the gas separation module is an air separation module comprised by an aircraft fuel tank flammability reduction system, the gas feed comprises an air feed, the first gas comprises oxygen, the second gas comprises nitrogen and the method further comprises:

supplying the retentate, which contains nitrogen-enriched air, to a fuel tank on board the aircraft.

11. The method of any of claims 9 to 10 further comprising exchanging heat between the feed flow path and the membrane flow path as enabled by the feed flow path being counter to the membrane flow path and, as a result, increasing a separation efficiency of the gas separation module.

12. The method of any of claims 9 to 11 further comprising establishing a temperature of the product end of the gas separation membrane that is within 10° F of a temperature of the feed end of the gas separation membrane.

13. The method of any of claims 9 to 12 further comprising providing a configuration for the gas separation module, selecting one or more process conditions, and, as a result, compensating for at least a portion of a temperature drop in the gas separation membrane due to enthalpy of gas separation.

14. The method of any of claims 9 to 13 wherein the housing comprises an inner shell and an outer shell, the gas separation membrane is within the inner shell, and flowing the gas feed along the feed flow path comprises flowing the gas feed along a passage between the inner shell and the outer shell, and wherein flowing the gas feed along the feed flow path or flowing the gas feed along the membrane flow path or both comprise flowing the gas feed along a plurality of separated flow paths.

15. The method of any of claims 9 to 14 wherein the gas separation membrane comprises a plurality of hollow fiber membranes, the gas separation module comprises a feed tubesheet within the housing securing the feed end of the plurality of hollow fiber membranes and a product tubesheet within the housing securing the product end of the plurality of hollow fiber membranes, and the method further comprises:

segregating the gas feed and the permeate exterior side of the plurality of hollow fiber membranes with the feed tubesheet; and

segregating the permeate exterior side of the plurality of hollow fiber membranes and the retentate with the product tubesheet, wherein the feed flow path extends among the plurality of hollow fiber membranes and the method further comprises segregating the feed flow path from contact with the permeate exterior side.

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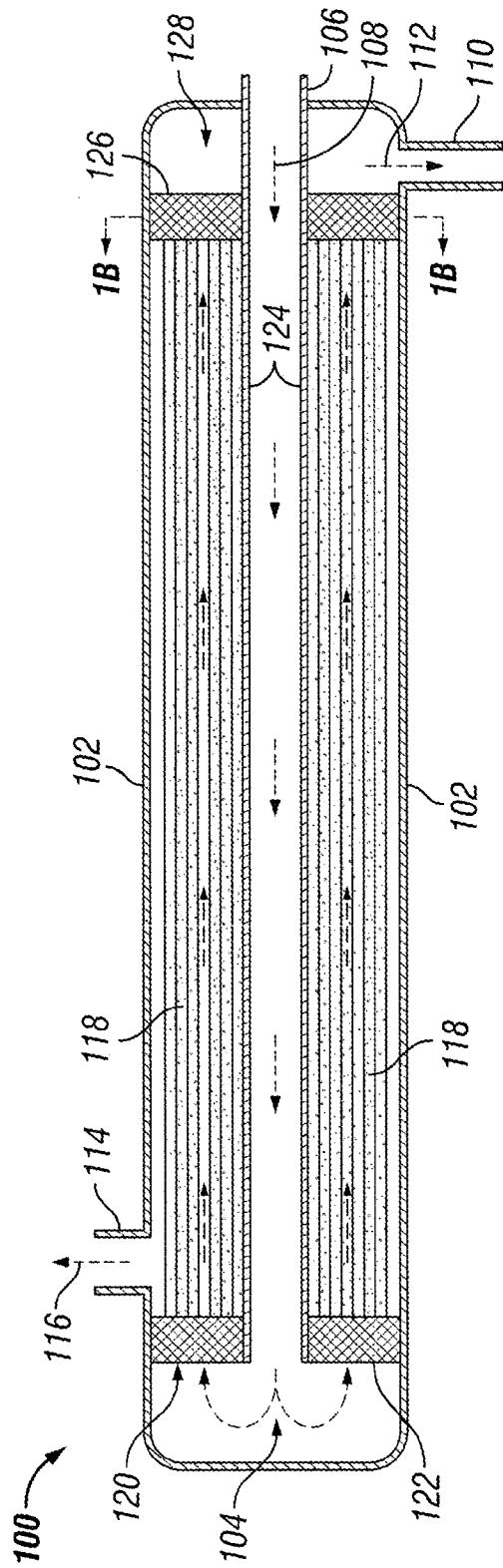


FIG. 1A

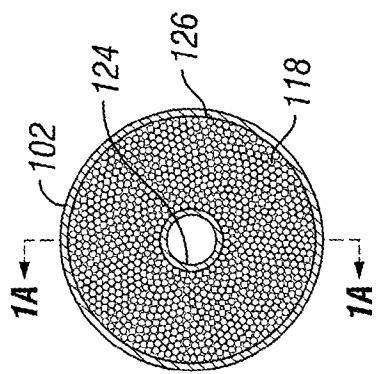


FIG. 1B

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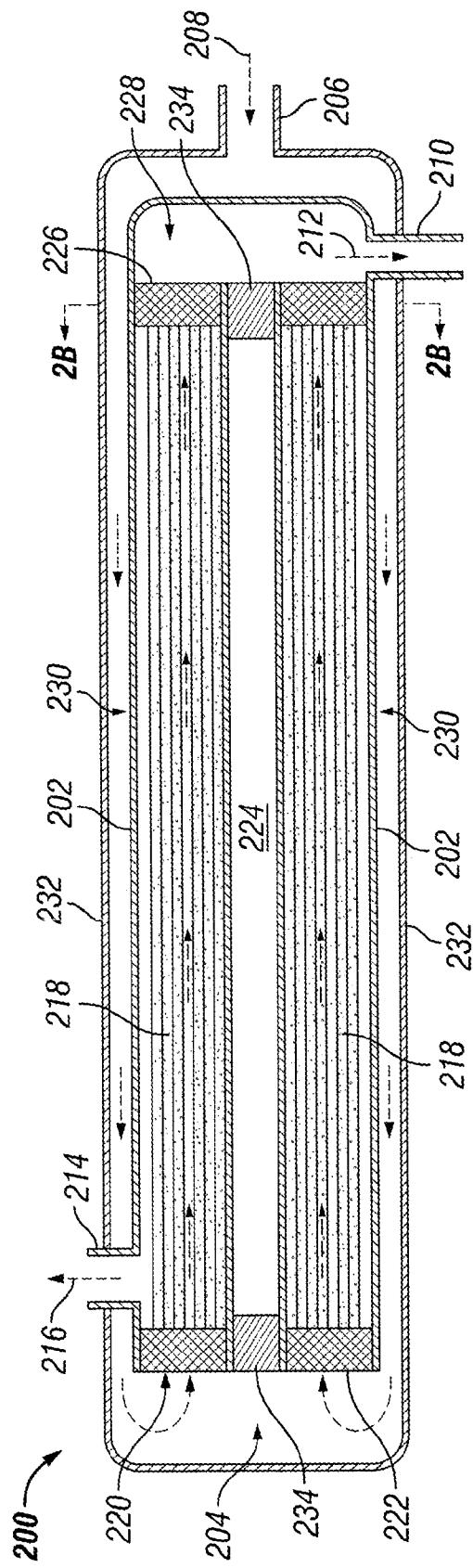


FIG. 2A

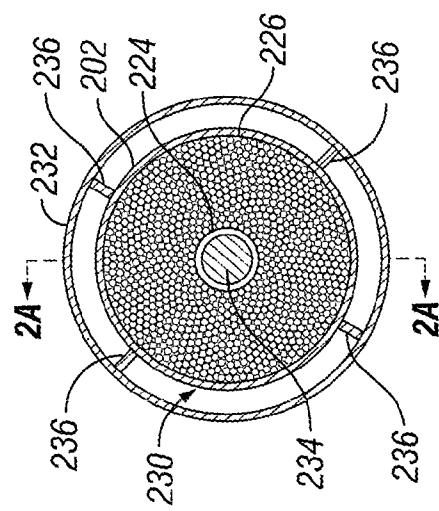
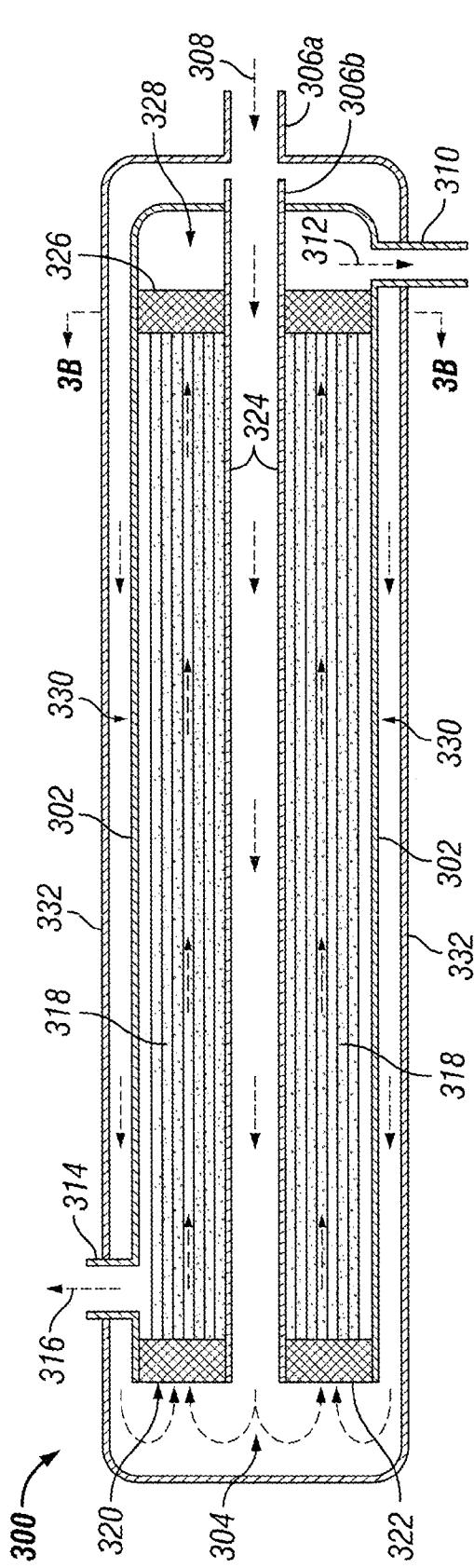


FIG. 2B



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FIG. 3A

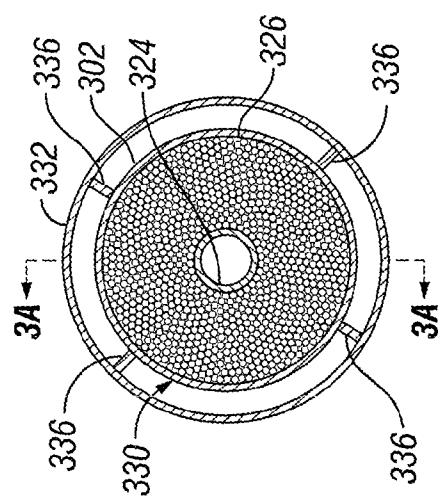


FIG. 3B

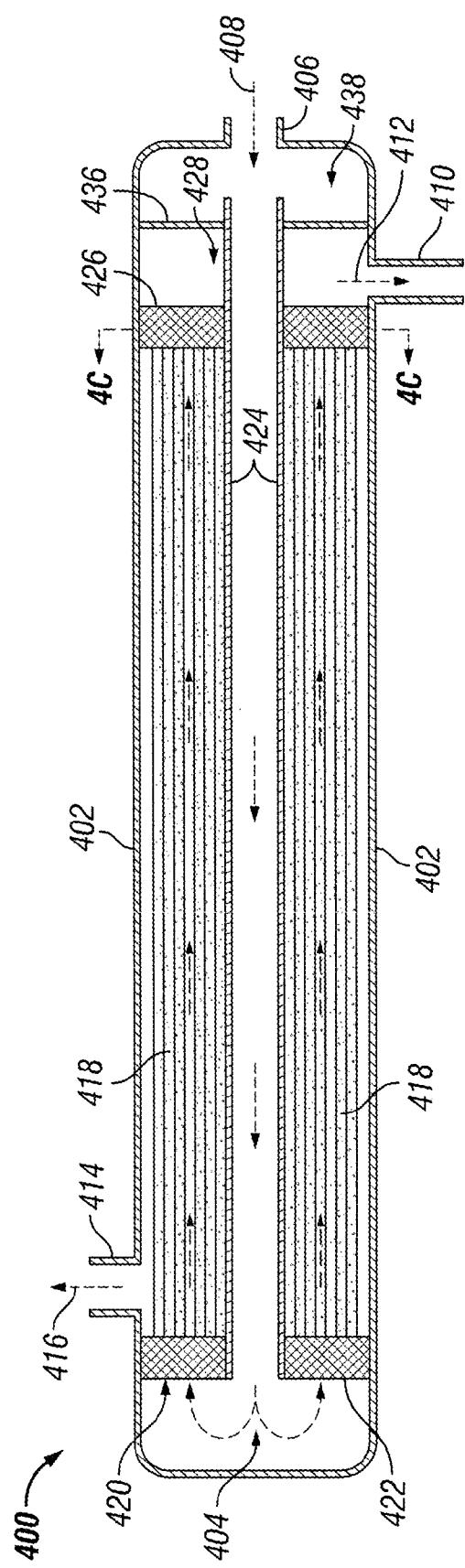


FIG. 4A

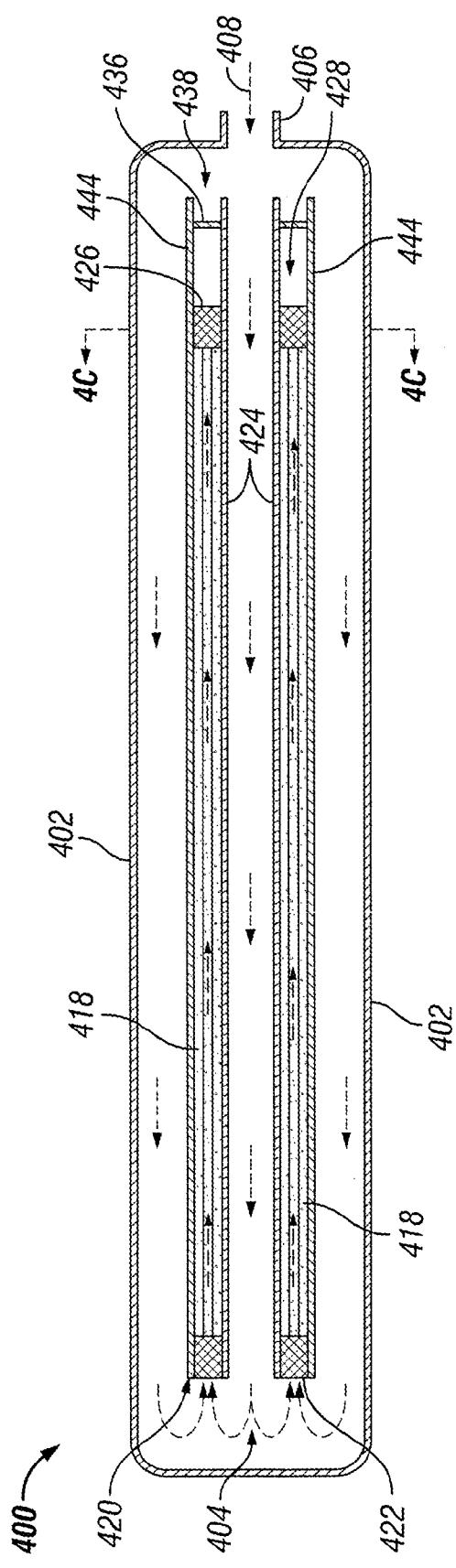


FIG. 4B

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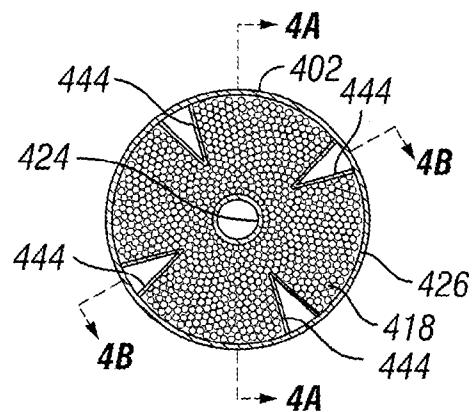
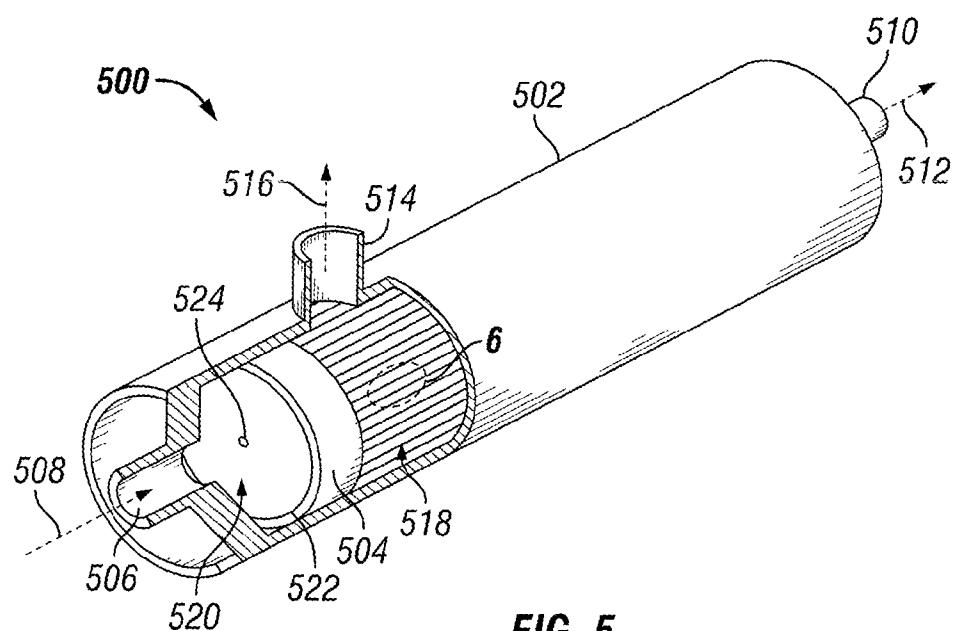
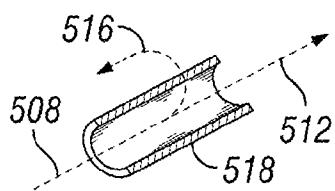


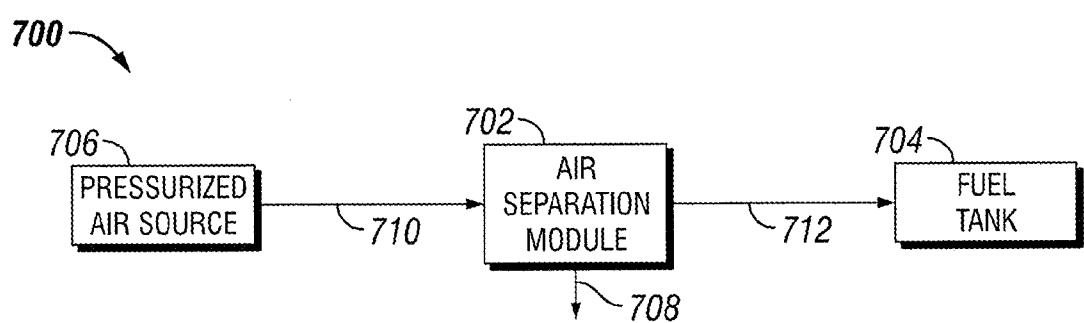
FIG. 4C

FIG. 5  
(Prior Art)

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**FIG. 6**  
(Prior Art)



**FIG. 7**

# INTERNATIONAL SEARCH REPORT

International application No  
PCT/US2014/010523

**A. CLASSIFICATION OF SUBJECT MATTER**  
INV. B01D53/22  
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)  
B01D

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, WPI Data

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

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X	US 5 411 662 A (NICOLAS JR PATRICK S [US] ET AL) 2 May 1995 (1995-05-02) figures 1-6	1,2,4-7, 9,11-14
		-/-

Further documents are listed in the continuation of Box C.

See patent family annex.

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- "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

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
26 March 2014	03/04/2014
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer  de Biasio, Arnaldo

**INTERNATIONAL SEARCH REPORT**International application No  
PCT/US2014/010523

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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**INTERNATIONAL SEARCH REPORT**

Information on patent family members

International application No

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