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(54) **HEAT AND MASS TRANSFER DEVICE AND SYSTEMS INCLUDING THE SAME**

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(73) Assignee: **BE POWER TECH LLC**, Parkland, FL (US)

(21) Appl. No.: **14/623,797**

(22) Filed: **Feb. 17, 2015**

Related U.S. Application Data

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F28D 7/10 (2006.01)

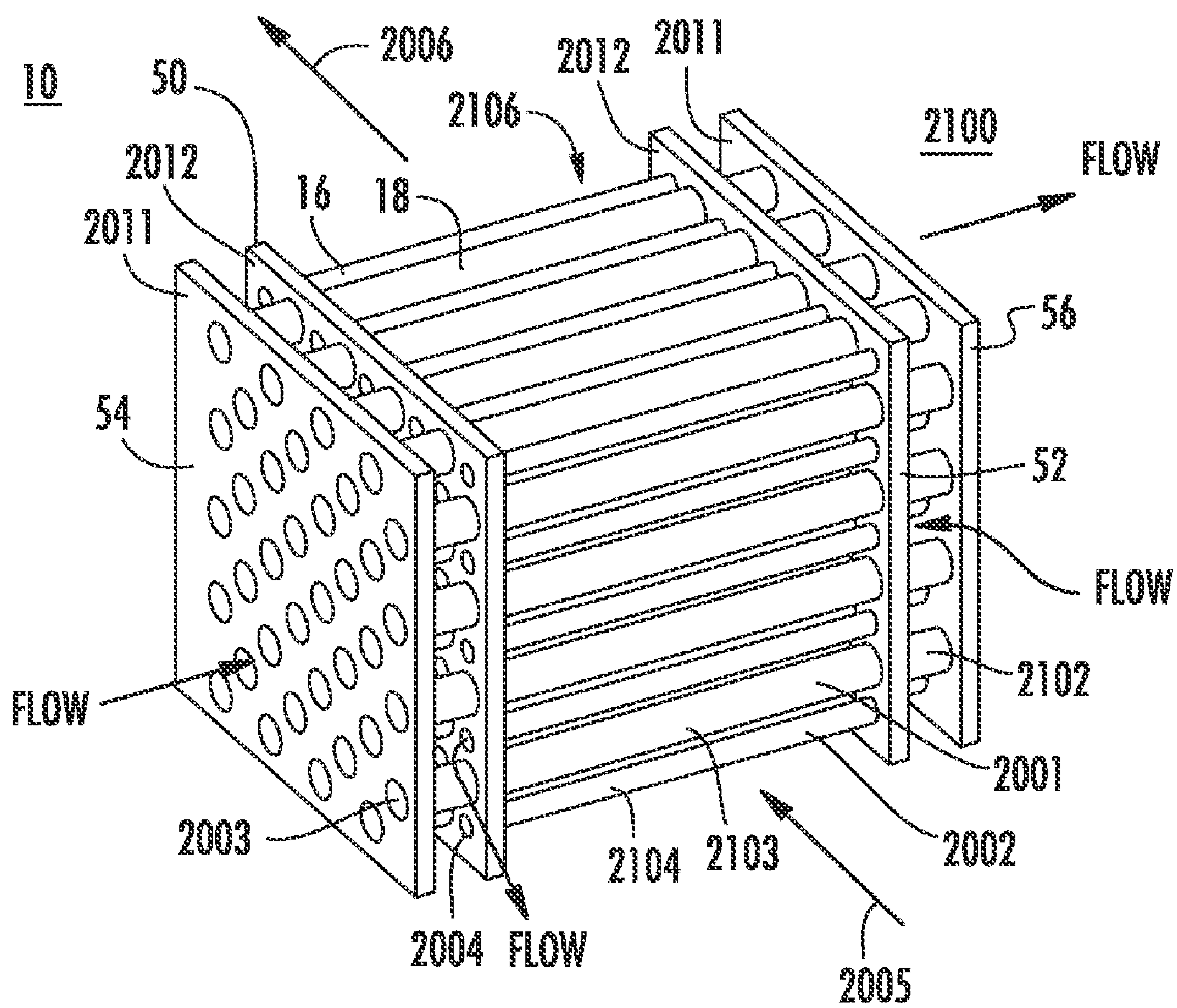
F24F 5/00 (2006.01)

(52) **U.S. Cl.**

CPC ***F24F 3/147*** (2013.01); ***F24F 5/0035*** (2013.01); ***F28D 7/10*** (2013.01)

(57) **ABSTRACT**

A heat and mass exchanger system is described. The heat and mass exchange system can include a plurality of exchange components extending across a heat and mass exchanger (HMX) duct, where a flow through the HMX duct is cross-flow relative to said exchange components. The exchange components can include a plurality of first elongated, hollow conduits and a plurality of second elongated, hollow conduit, where either the first elongated, hollow conduits or the second elongated, hollow conduits have water vapor permeable exterior walls, and a carrier air stream and a liquid desiccant stream flow in contact with opposite sides of the water vapor permeable exterior walls.



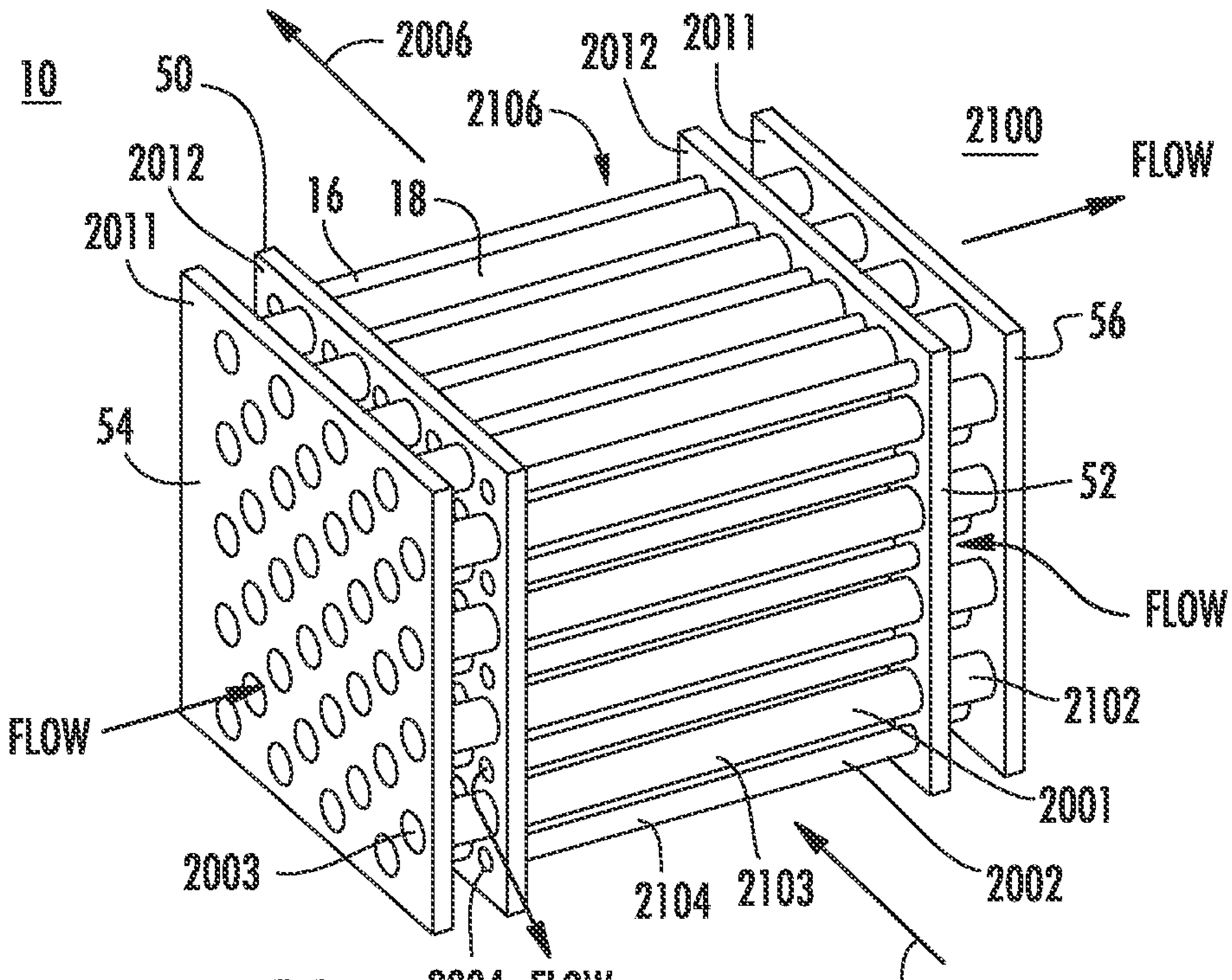

10
50
2006
2012
2011
2106
2012
2011
2100
FLOW
16
18
56
54
52
FLOW
FLOW
2102
2001
2003
2002
2104
2103
2004
FLOW
2005

FIG. 1A

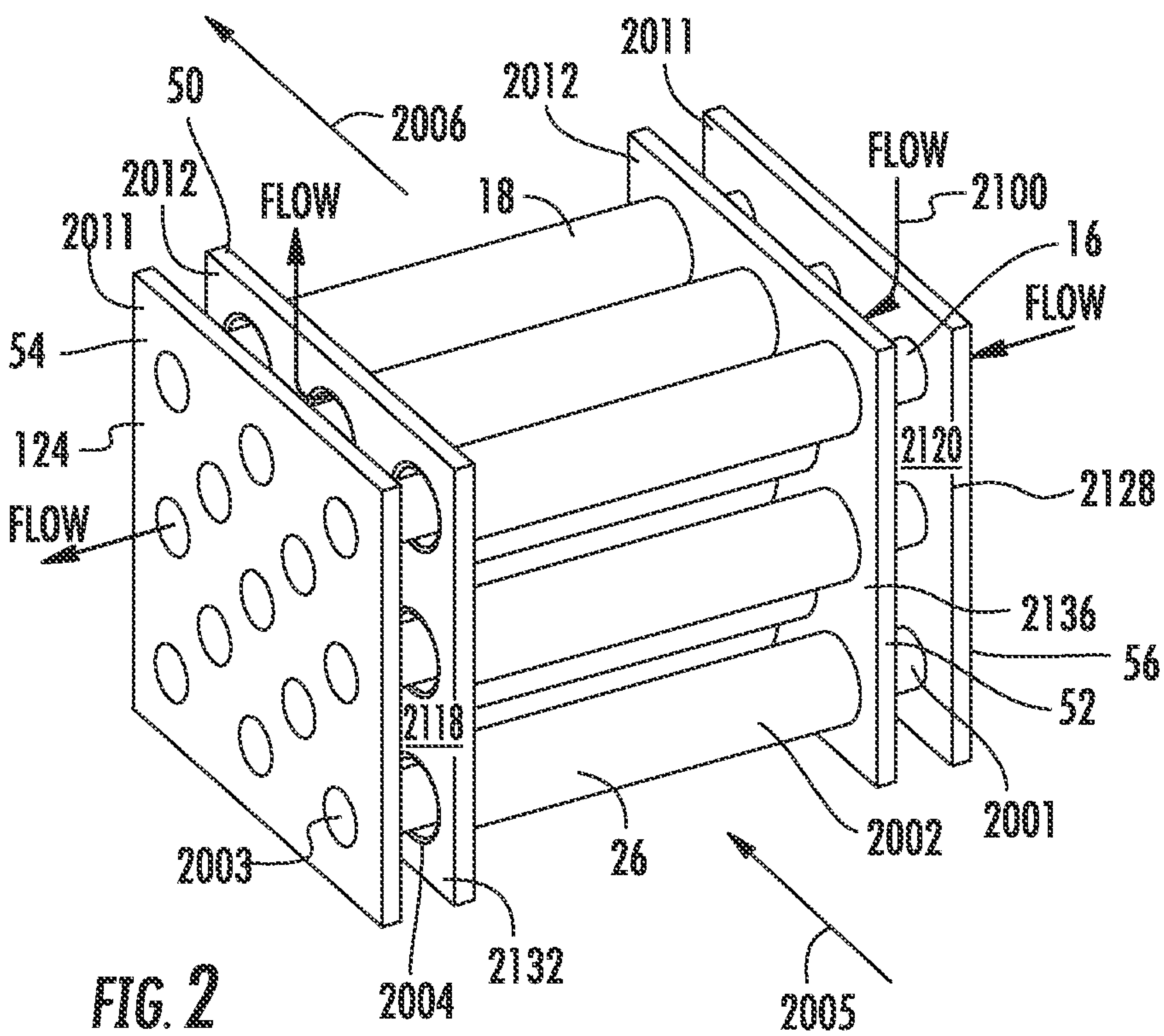

2011
2006
2012
50
2012
2011
FLOW
18
FLOW
2100
16
FLOW
54
124
2120
2128
FLOW
2136
56
52
2118
2001
2003
26
2002
2132
2004
2005

FIG. 2

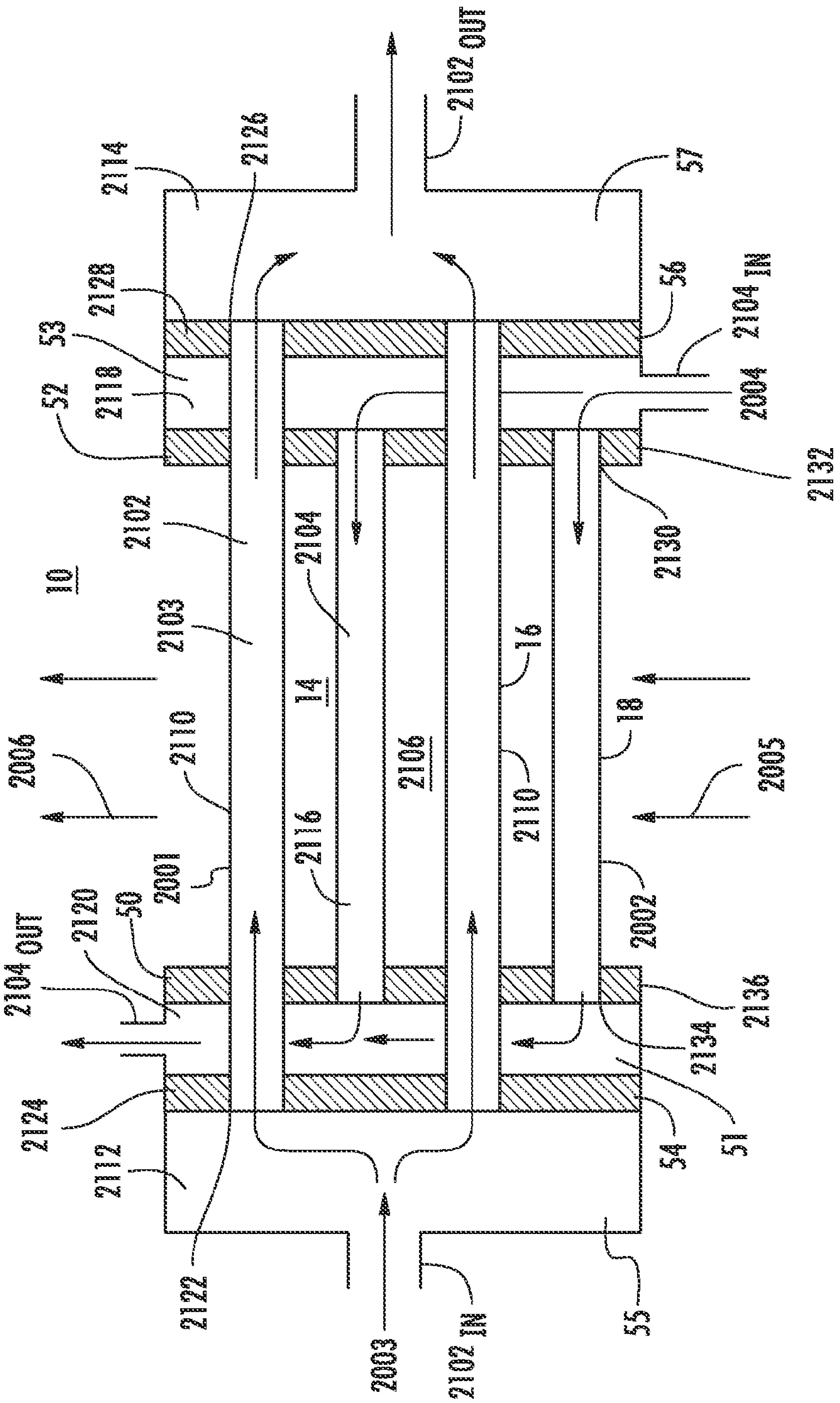

2102 OUT
2114
2126
57
2128
53
56
2104 IN
2118
52
2004
2132
2102
2130
10
2103
2104
14
16
2106
2110
2110
18
2006
2005
2116
2001
2002
2104 OUT
2120
50
2136
2134
2124
2112
54
51
2122
55
2003
2102 IN

FIG. 1B

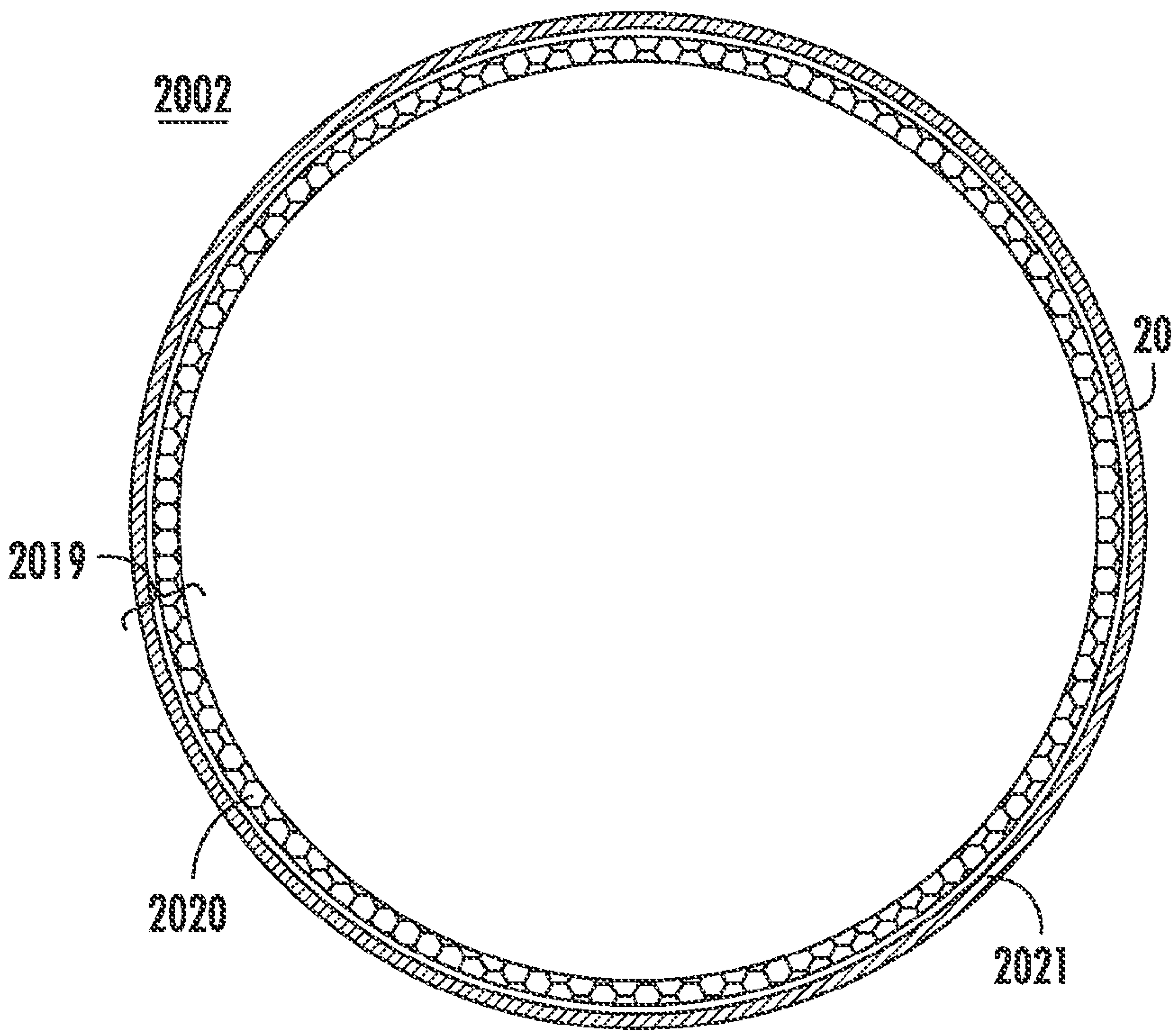


FIG. 3

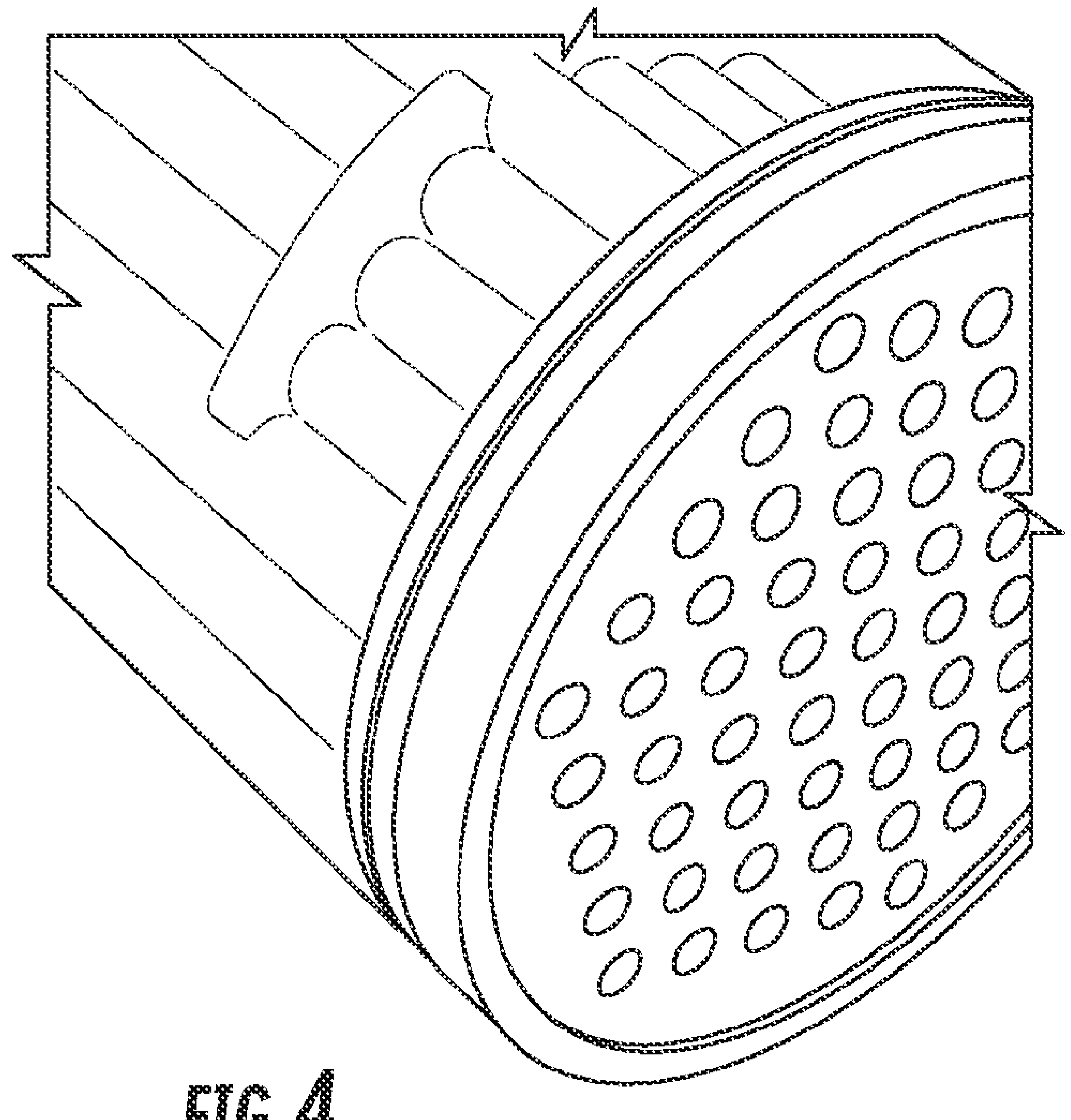


FIG. 4

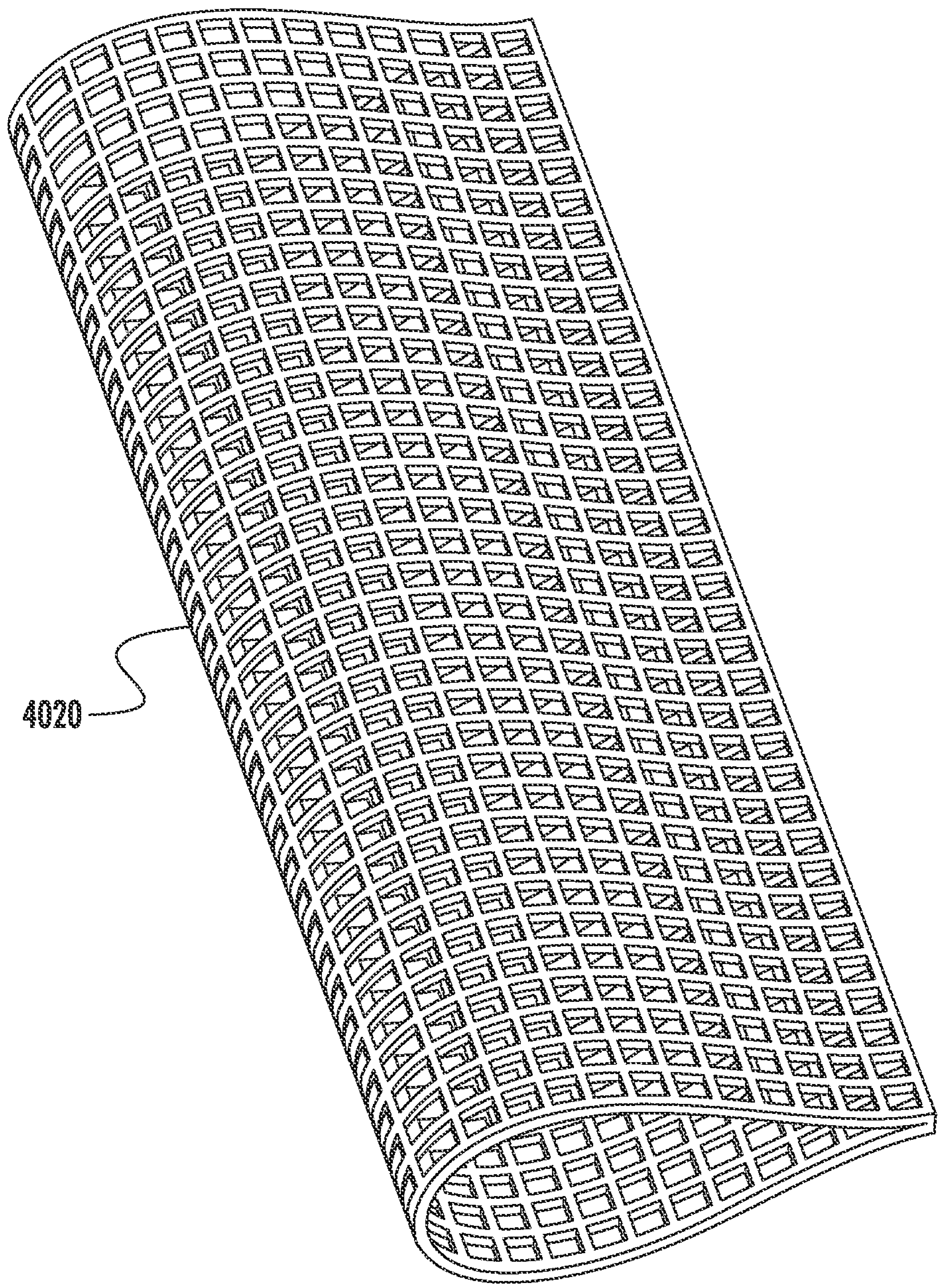
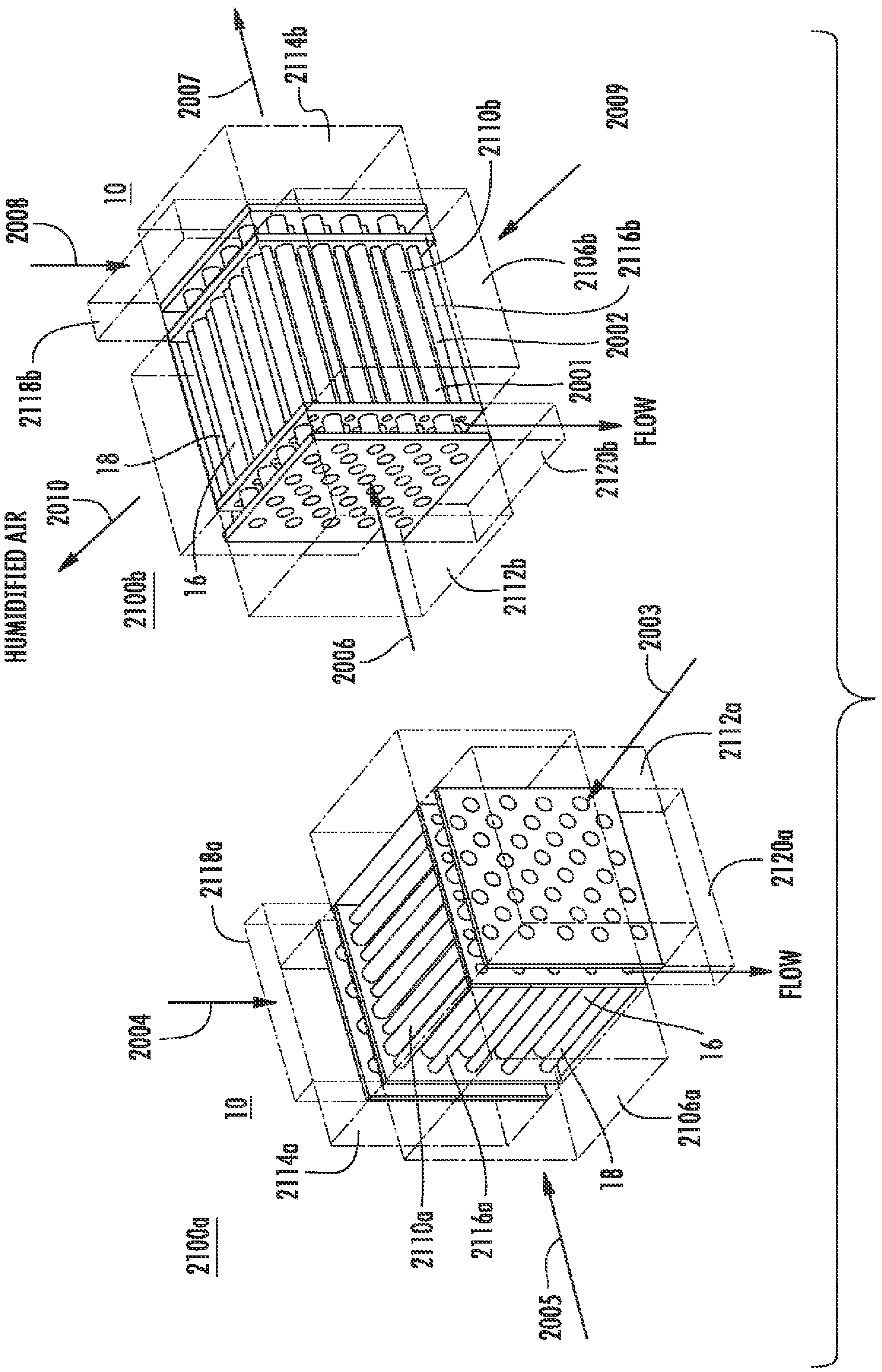
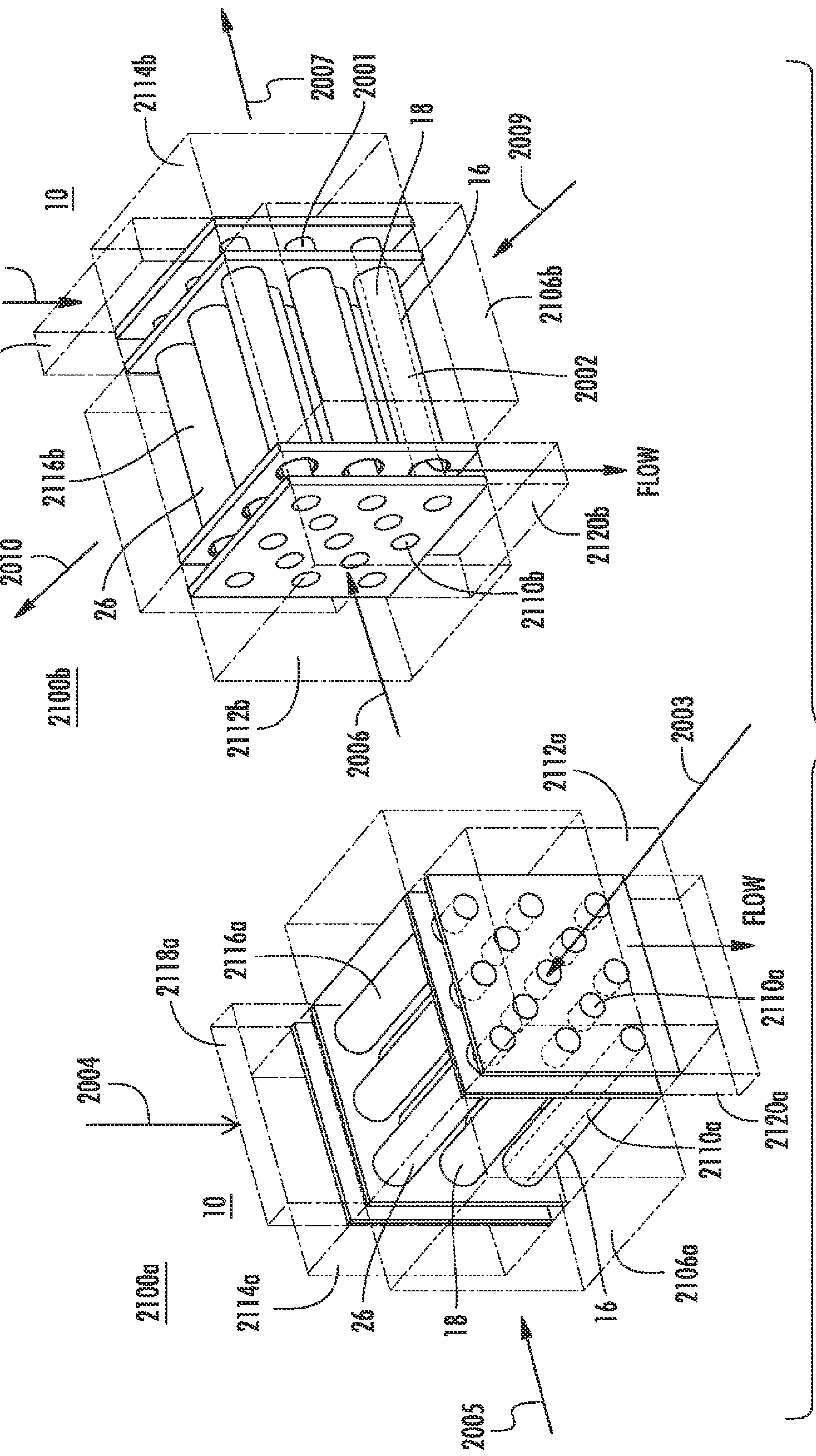


FIG. 5



2100a
10
2004
2118a
2114a
2110a
2116a
2106a
18
16
2005
2120a
2112a
2003
FLOW
2100b
HUMIDIFIED AIR
2010
2008
2118b
18
16
2112b
2006
2120b
FLOW
2001
2002
2116b
2106b
2110b
2009
2114b
2007

FIG. 6



2100b
10
2008
2118b
2116b
2010
26
2112b
2006
2120b
2110b
FLOW
2002
2106b
16
18
2009
2001
2007
2114b
2100a
2114a
26
18
16
2106a
2005
10
2004
2118a
2116a
2110a
2120a
2112a
2003
FLOW

FIG. 7

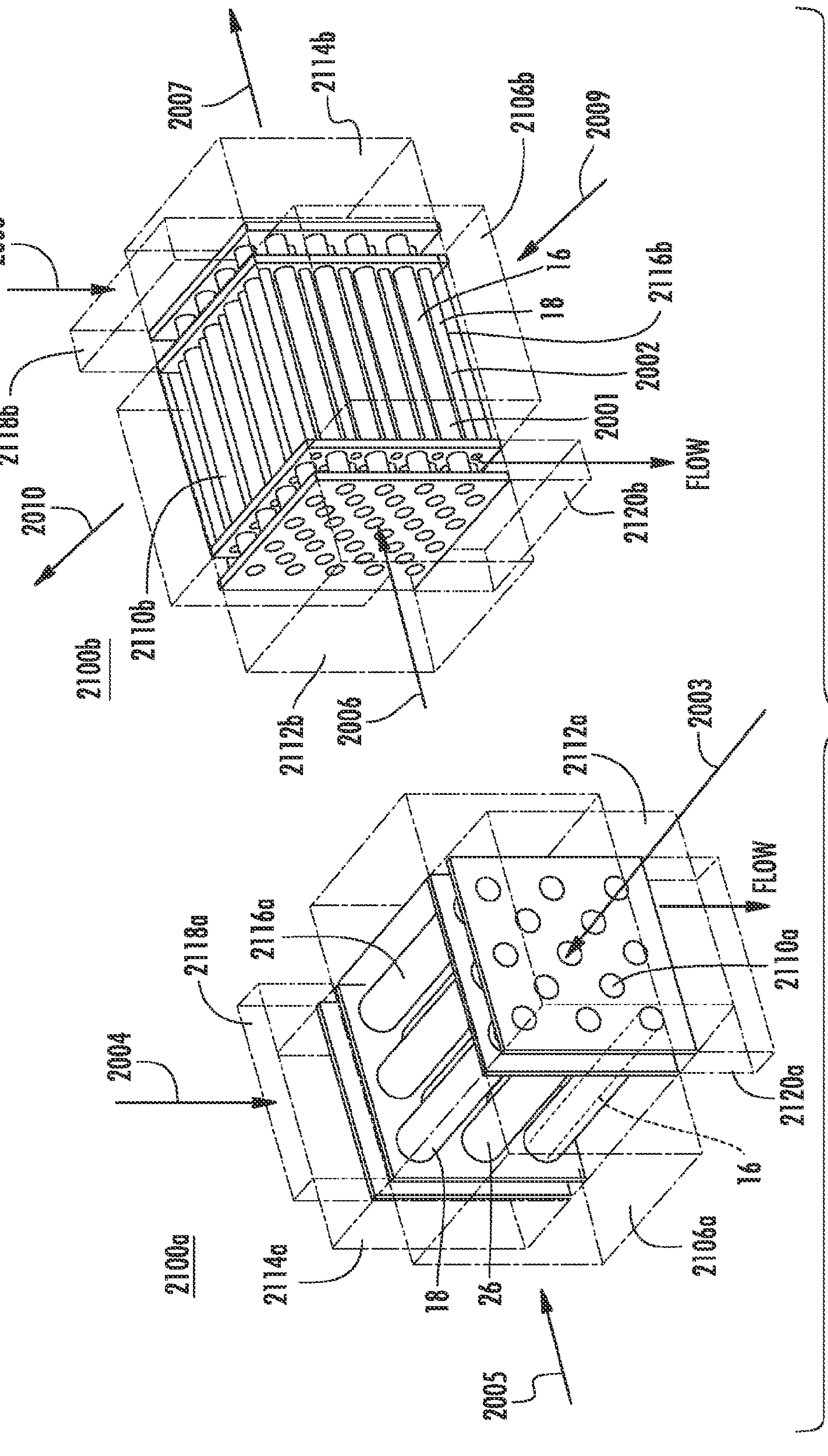

2100a
2114a
18
26
2106a
2005
2004
2118a
2116a
2110a
2120a
16
2112a
2003
FLOW
2100b
2110b
2010
2118b
2008
2001
2002
2116b
18
16
2009
2106b
2007
2114b
2112b
2006
2120b
FLOW

FIG. 8

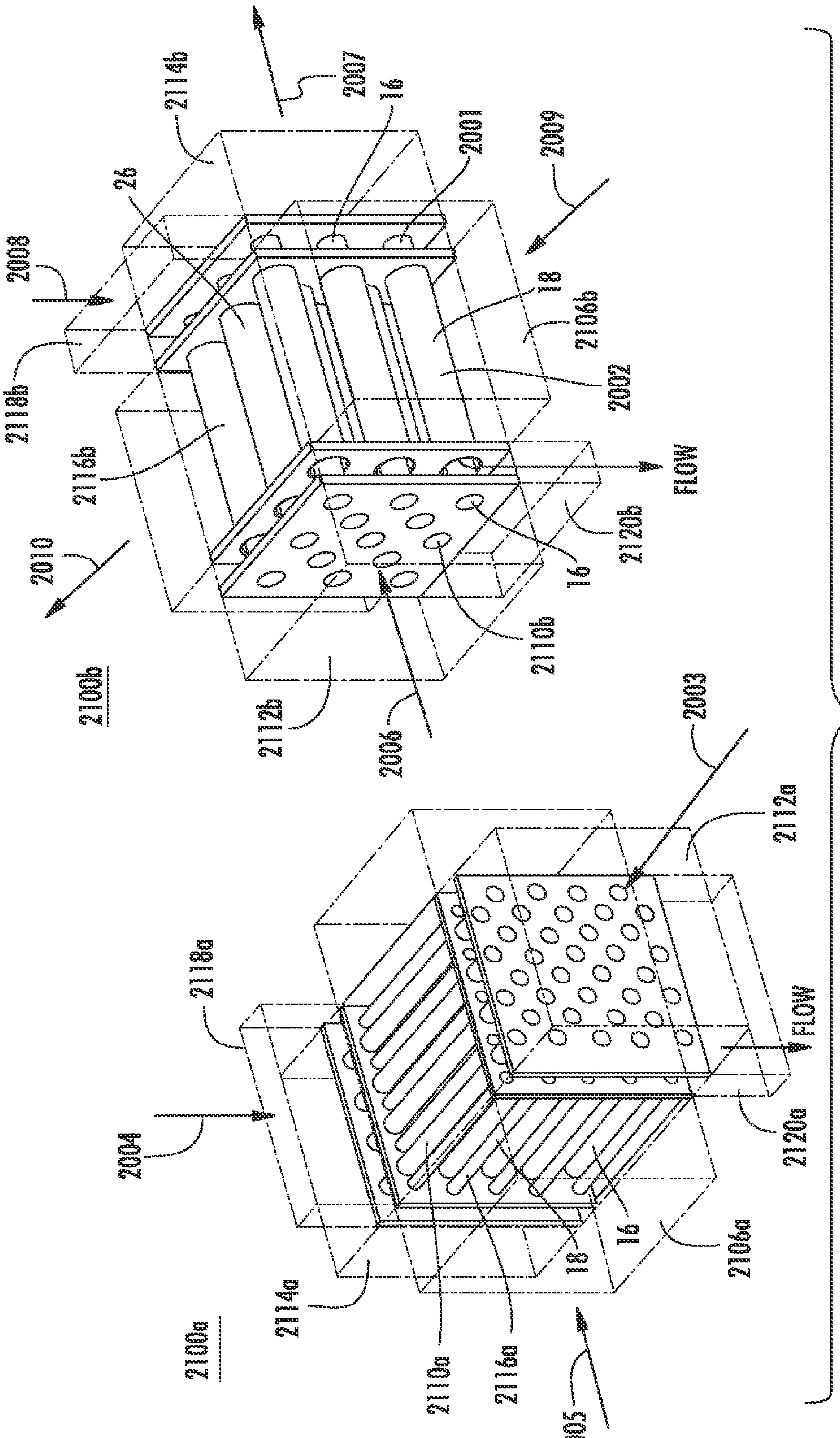

2100b
2114b
2007
16
2001
2009
26
2008
2118b
2116b
18
2106b
2002
FLOW
2010
2120b
16
2110b
2112b
2006
2100a
2003
2112a
2118a
2004
FLOW
2120a
2114a
18
16
2106a
2110a
2116a
2005

FIG. 9

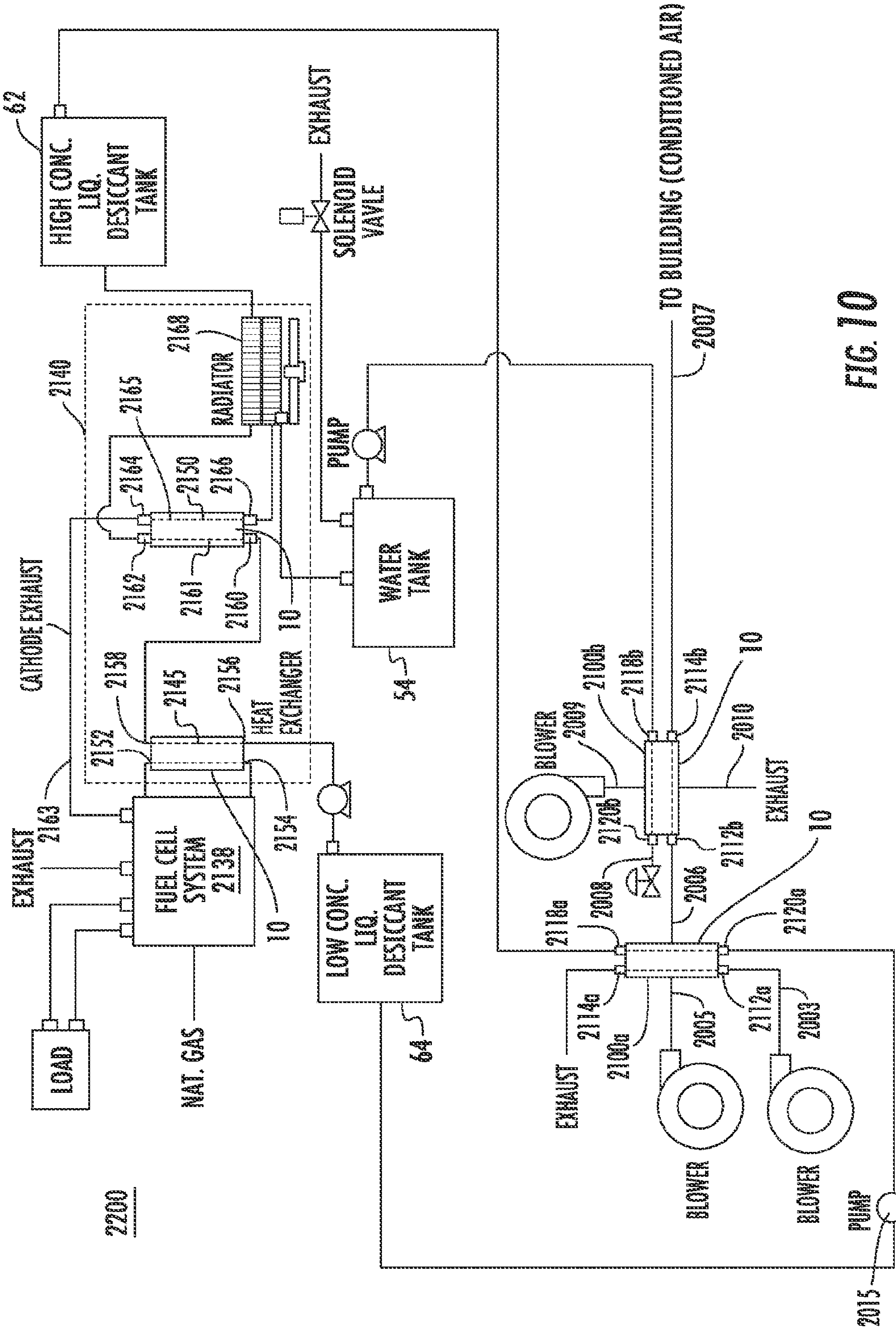

2200
LOAD
NAT. GAS
EXHAUST
2163
FUEL CELL SYSTEM 2138
CATHODE EXHAUST
2152
2158
2145
2156
HEAT EXCHANGER
2154
10
2140
2162
2161
2160
2164
2150
2166
2165
RADIATOR
2168
HIGH CONC. LIQ. DESICCANT TANK
62
SOLENOID VAVLE
EXHAUST
PUMP
WATER TANK
54
LOW CONC. LIQ. DESICCANT TANK
64
TO BUILDING (CONDITIONED AIR)
2007
BLOWER
2009
2100b
2118b
2114b
2010
EXHAUST
2120b
2112b
2008
2006
2118a
2120a
2114a
2100a
2005
2112a
2003
BLOWER
BLOWER
PUMP
2015

FIG. 10

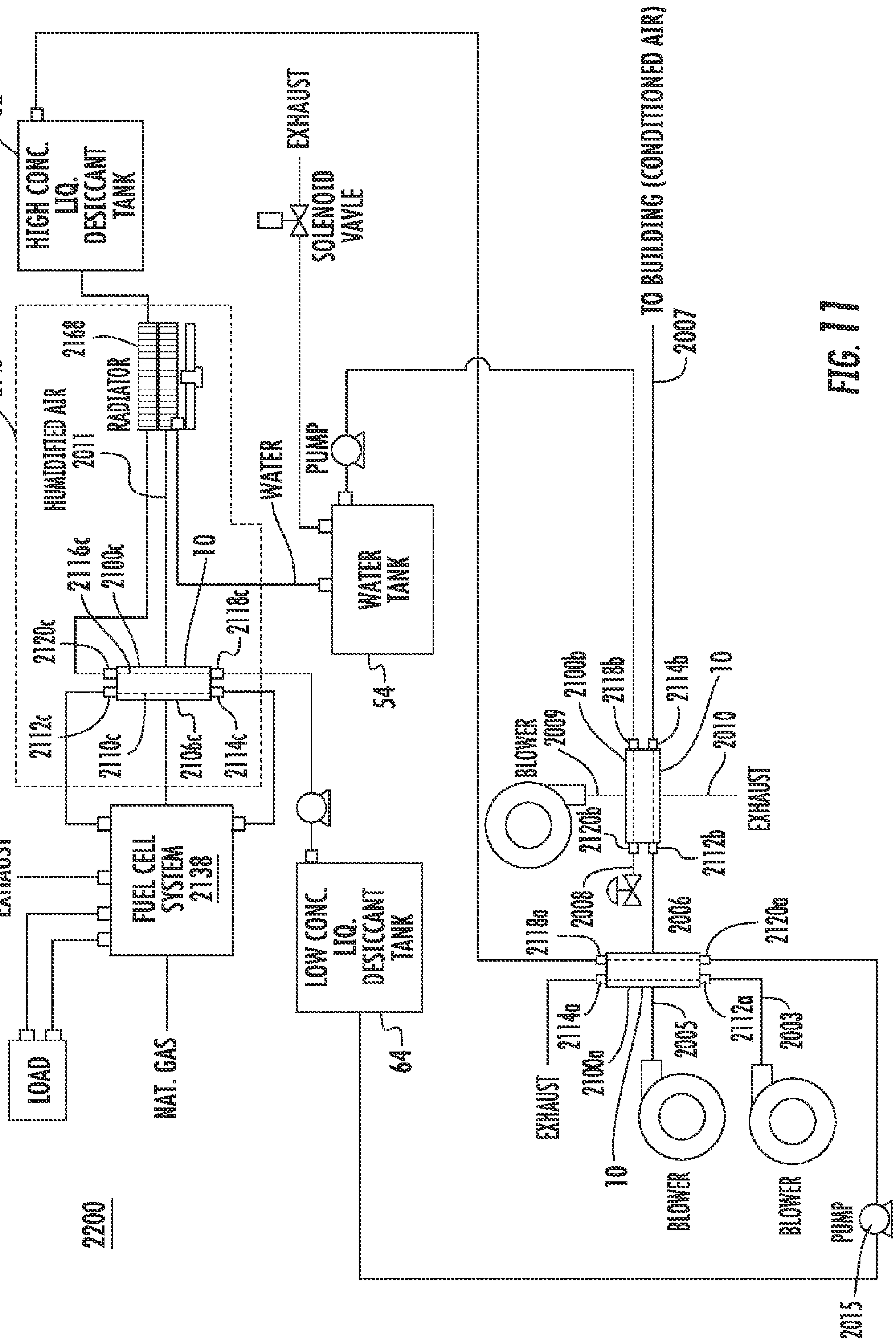
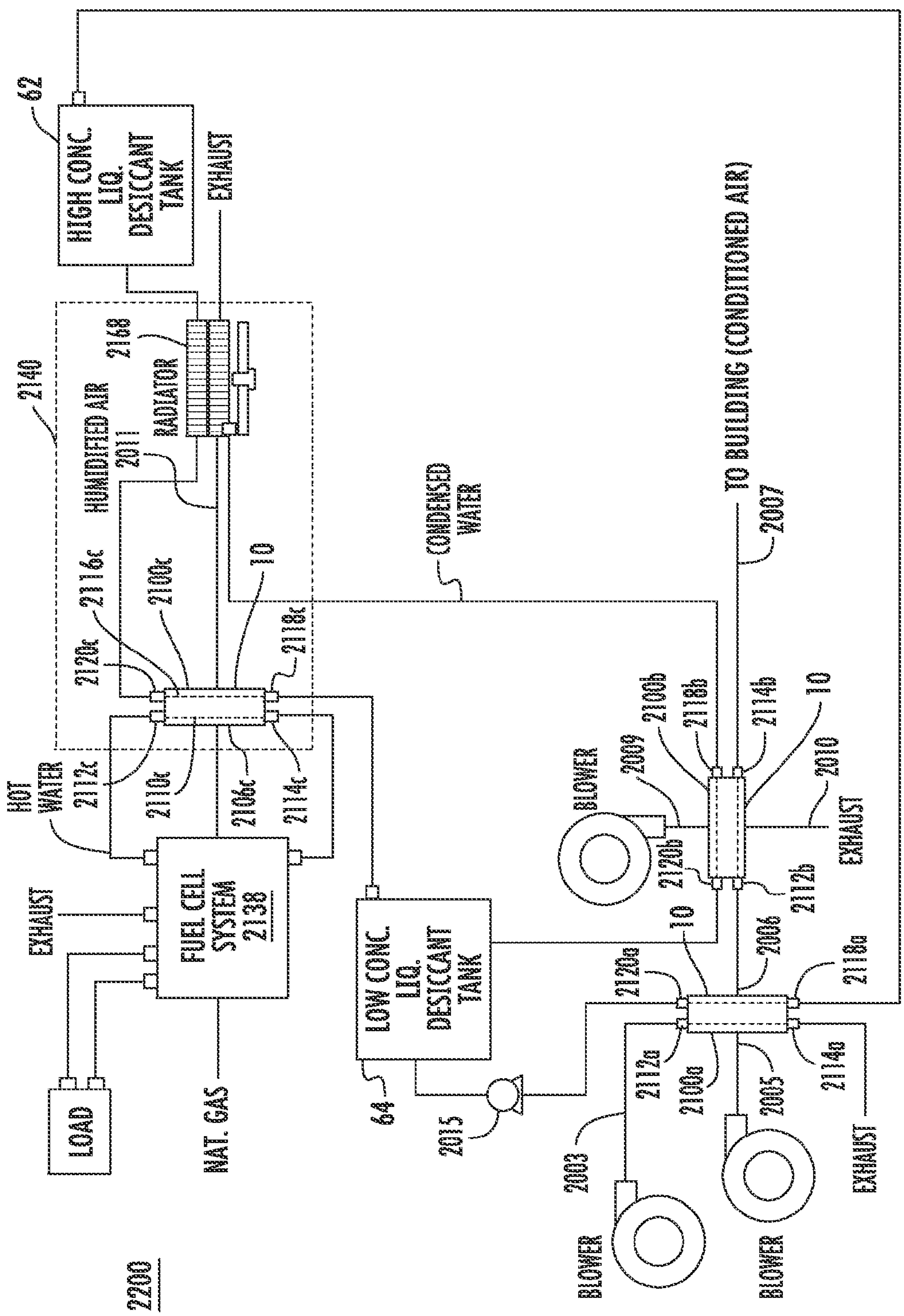

2200
LOAD
NAT. GAS
EXHAUST
FUEL CELL SYSTEM 2138
LOW CONC. LIQ. DESICCANT TANK
64
HIGH CONC. LIQ. DESICCANT TANK
62
2140
HUMIDIFIED AIR 2011
RADIATOR
2168
WATER
WATER TANK
54
PUMP
SOLENOID VAVLE
EXHAUST
TO BUILDING (CONDITIONED AIR)
2007
2112c
2110c
2106c
2114c
2120c
2116c
2100c
10
2118c
BLOWER
2009
2100b
2118b
2114b
10
2010
EXHAUST
2120b
2112b
2008
2006
2118a
2120a
2114a
2100a
2005
2112a
2003
EXHAUST
10
BLOWER
BLOWER
PUMP
2015

FIG. 11


2200
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EXHAUST
FUEL CELL SYSTEM 2138
HOT WATER
2112c
2110c
2106c
2114c
2120c
2116c
2100c
10
2118c
2140
HUMIDIFIED AIR
2011
RADIATOR
2168
EXHAUST
HIGH CONC. LIQ. DESICCANT TANK
62
LOW CONC. LIQ. DESICCANT TANK
64
2015
CONDENSED WATER
TO BUILDING (CONDITIONED AIR)
2007
BLOWER
2009
2100b
2118b
2114b
10
2010
EXHAUST
2120b
2112b
2006
10
2120a
2118a
2112a
2100a
2005
2114a
2003
BLOWER
BLOWER
EXHAUST

FIG. 12

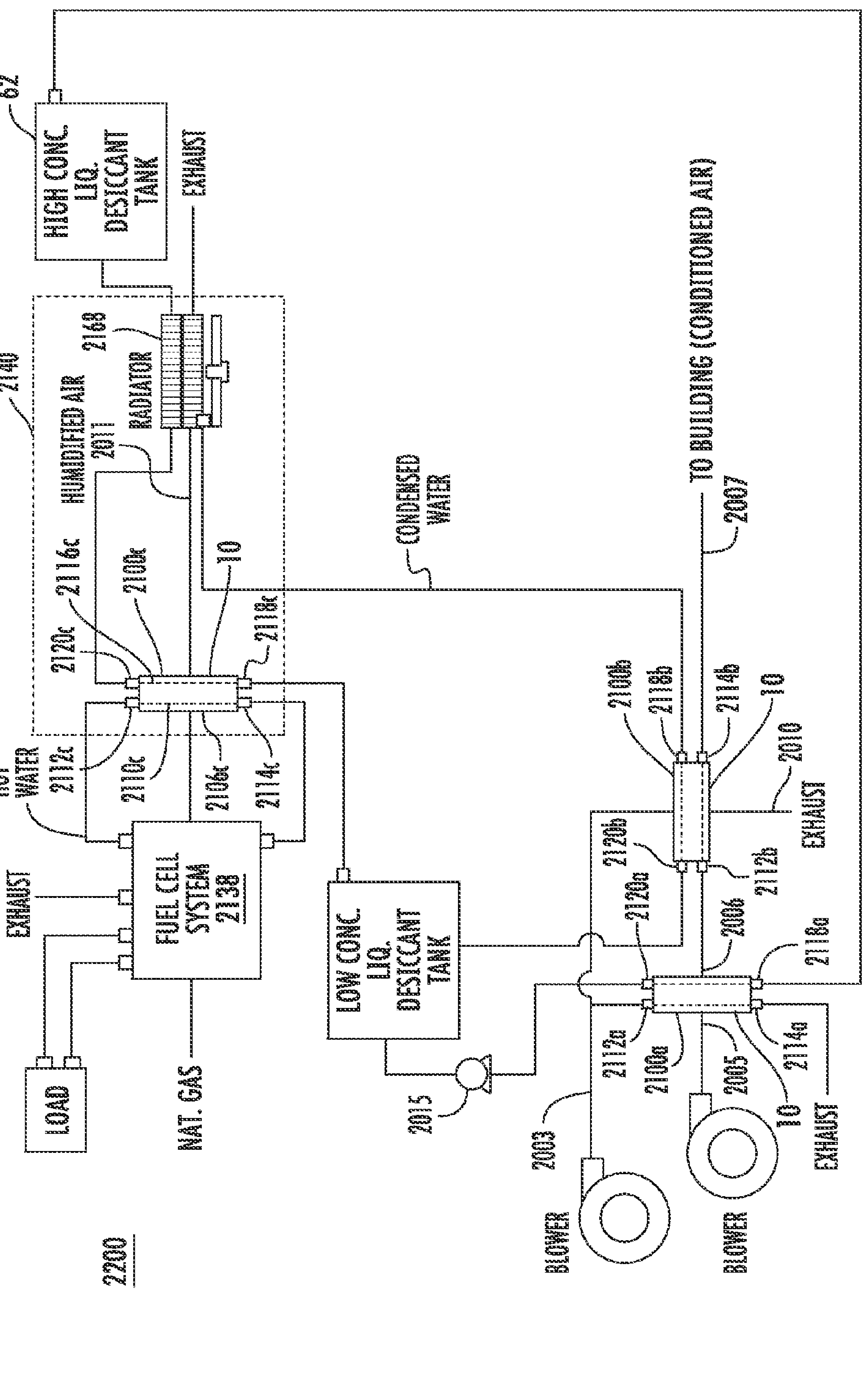

HIGH CONC. LIQ. DESICCANT TANK
62
EXHAUST
2140
HUMIDIFIED AIR
RADIATOR
2168
2011
2120c
2116c
2100c
10
2118c
CONDENSED WATER
TO BUILDING (CONDITIONED AIR)
2007
HOT WATER
2112c
2110c
2106c
2114c
EXHAUST
FUEL CELL SYSTEM 2138
LOAD
NAT. GAS
LOW CONC. LIQ. DESICCANT TANK
2015
2100b
2118b
2114b
10
2010
EXHAUST
2120b
2112b
2120a
2006
2118a
2112a
2100a
2005
10
2114a
EXHAUST
2003
BLOWER
BLOWER
2200

FIG. 13

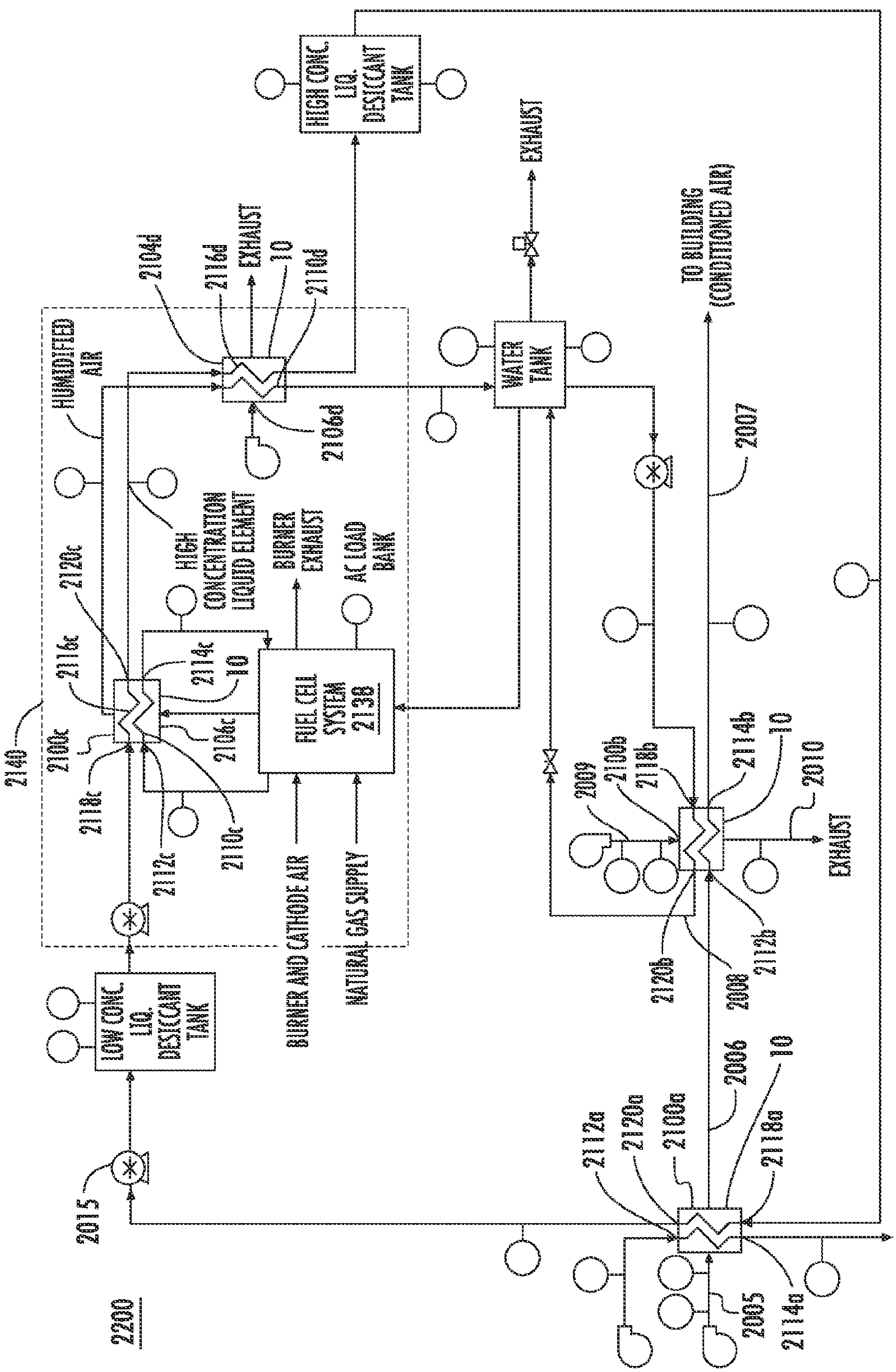

2200
2015
LOW CONC. LIQ. DESICCANT TANK
2140
2100c
2118c
2112c
2110c
2116c
2120c
2114c
10
2106c
FUEL CELL SYSTEM 2138
BURNER AND CATHODE AIR
NATURAL GAS SUPPLY
HIGH CONCENTRATION LIQUID ELEMENT
BURNER EXHAUST
AC LOAD BANK
HUMIDIFIED AIR
2104d
2116d
EXHAUST
10
2118d
2106d
HIGH CONC. LIQ. DESICCANT TANK
WATER TANK
EXHAUST
TO BUILDING (CONDITIONED AIR)
2007
2009
2100b
2118b
2114b
10
2010
EXHAUST
2120b
2008
2112b
2006
10
2112a
2120a
2100a
2118a
2005
2114a
EXHAUST

FIG. 14

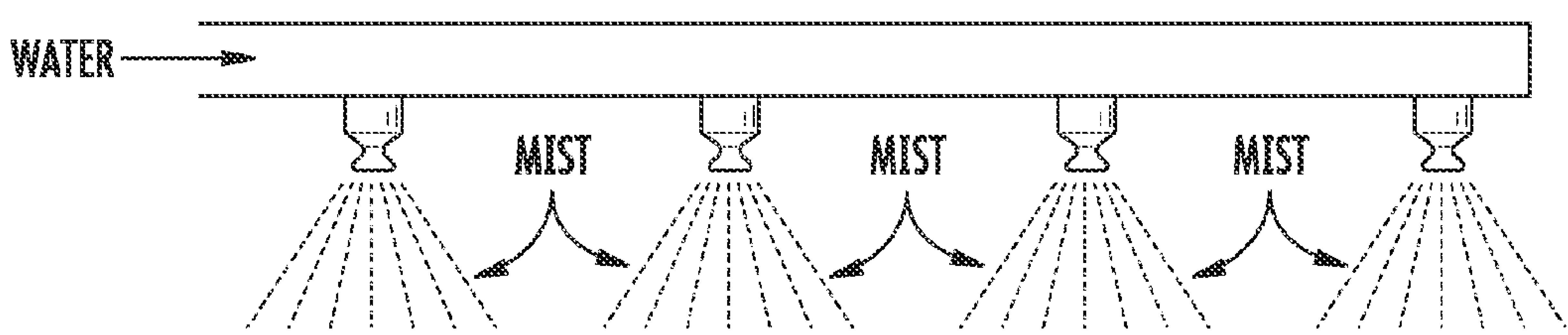
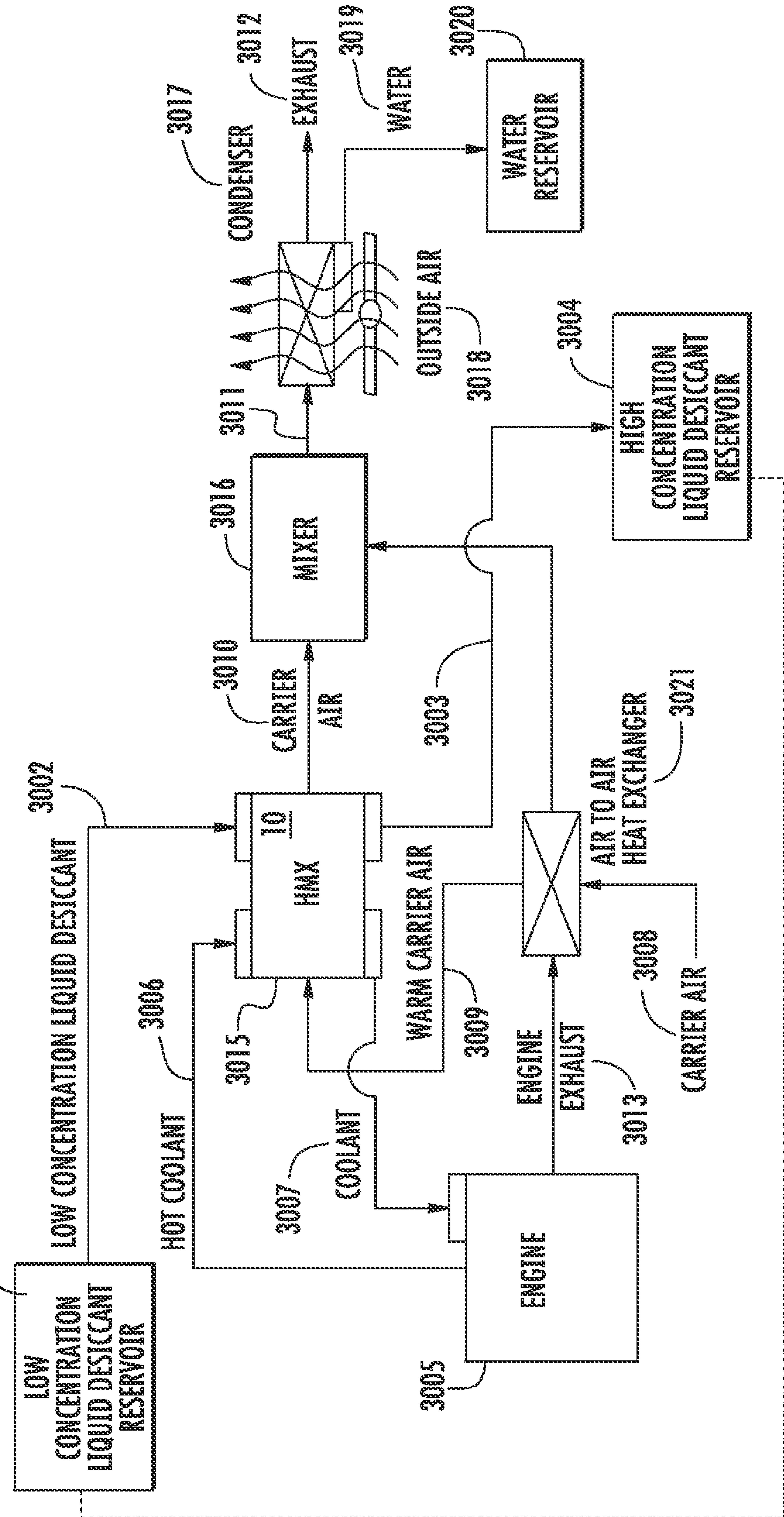
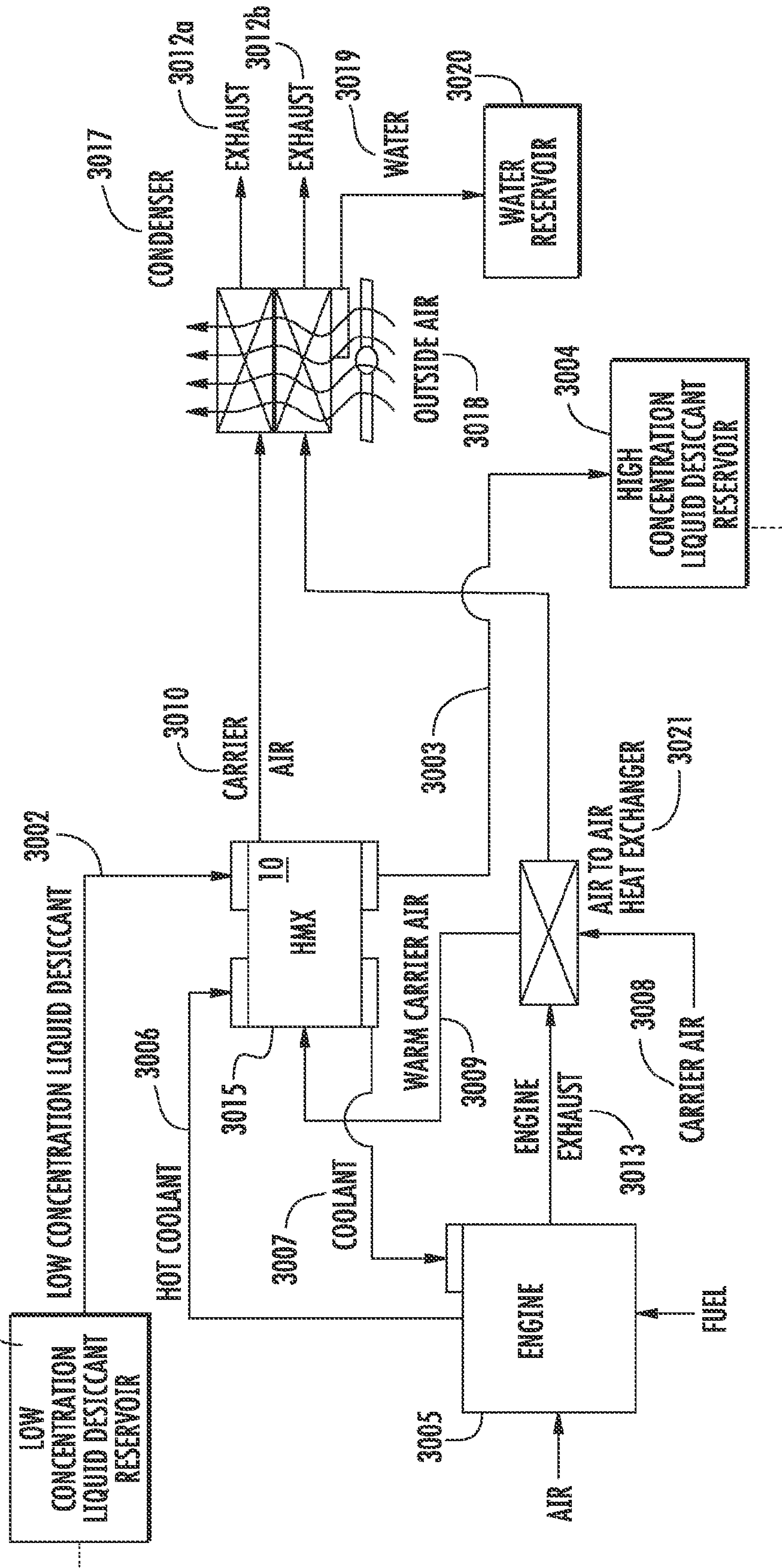


FIG. 15



LOW CONCENTRATION LIQUID DESICCANT RESERVOIR
3001
LOW CONCENTRATION LIQUID DESICCANT
3002
HOT COOLANT
3006
COOLANT
3007
HMX
10
3015
WARM CARRIER AIR
3009
ENGINE
3005
ENGINE EXHAUST
3013
AIR TO AIR HEAT EXCHANGER
3021
CARRIER AIR
3008
CARRIER AIR
3010
3003
MIXER
3016
3011
CONDENSER
3017
EXHAUST
3012
OUTSIDE AIR
3018
WATER
3019
WATER RESERVOIR
3020
HIGH CONCENTRATION LIQUID DESICCANT RESERVOIR
3004

FIG. 16



3001
LOW CONCENTRATION LIQUID DESICCANT RESERVOIR
3002
LOW CONCENTRATION LIQUID DESICCANT
3006
HOT COOLANT
3007
COOLANT
3005
ENGINE
AIR
FUEL
3015
HMX
10
3009
WARM CARRIER AIR
3013
ENGINE EXHAUST
3008
CARRIER AIR
AIR TO AIR HEAT EXCHANGER
3021
3010
CARRIER AIR
3003
3004
HIGH CONCENTRATION LIQUID DESICCANT RESERVOIR
3018
OUTSIDE AIR
3017
CONDENSER
3012a
EXHAUST
3012b
EXHAUST
3019
WATER
3020
WATER RESERVOIR

FIG. 17

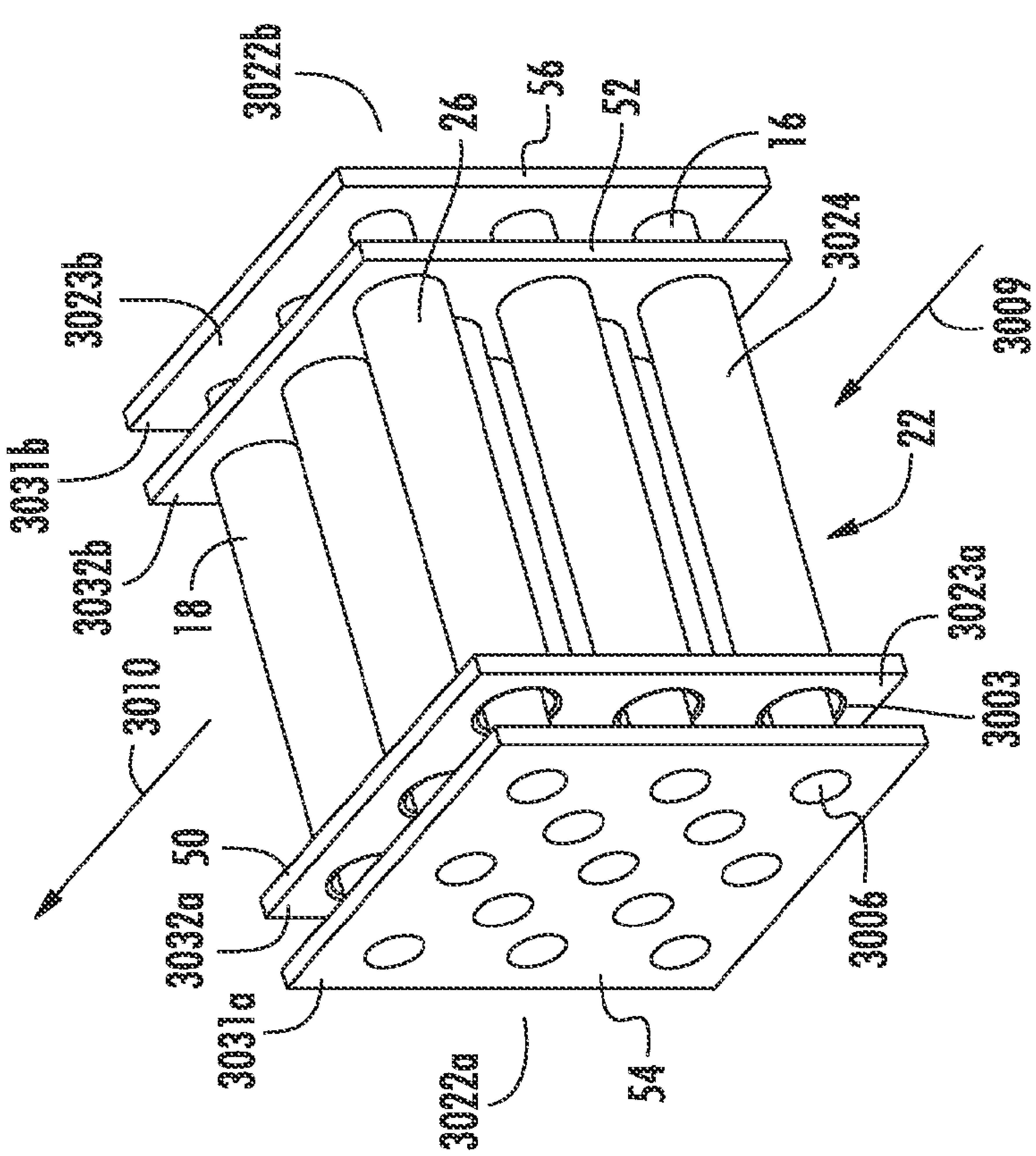

3022b
56
52
16
26
3023b
3024
3031b
3009
22
3032b
18
3023a
3010
3003
50
3032a
3006
3031a
3022a
54

FIG. 19

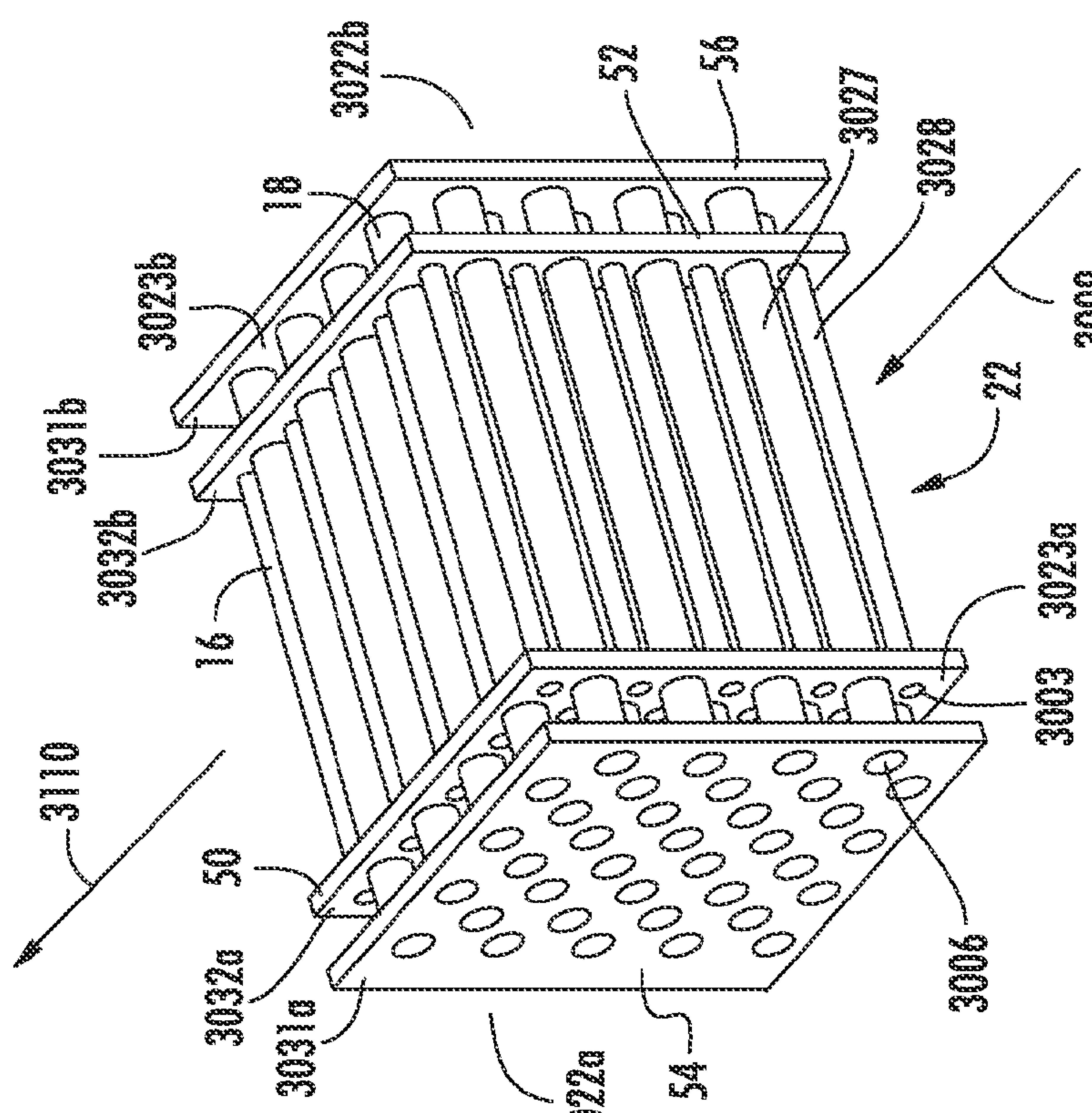

3022b
52
56
3027
18
3028
3023b
3031b
3009
22
3032b
16
3023a
3110
3003
50
3032a
3006
3031a
3022a
54

FIG. 18

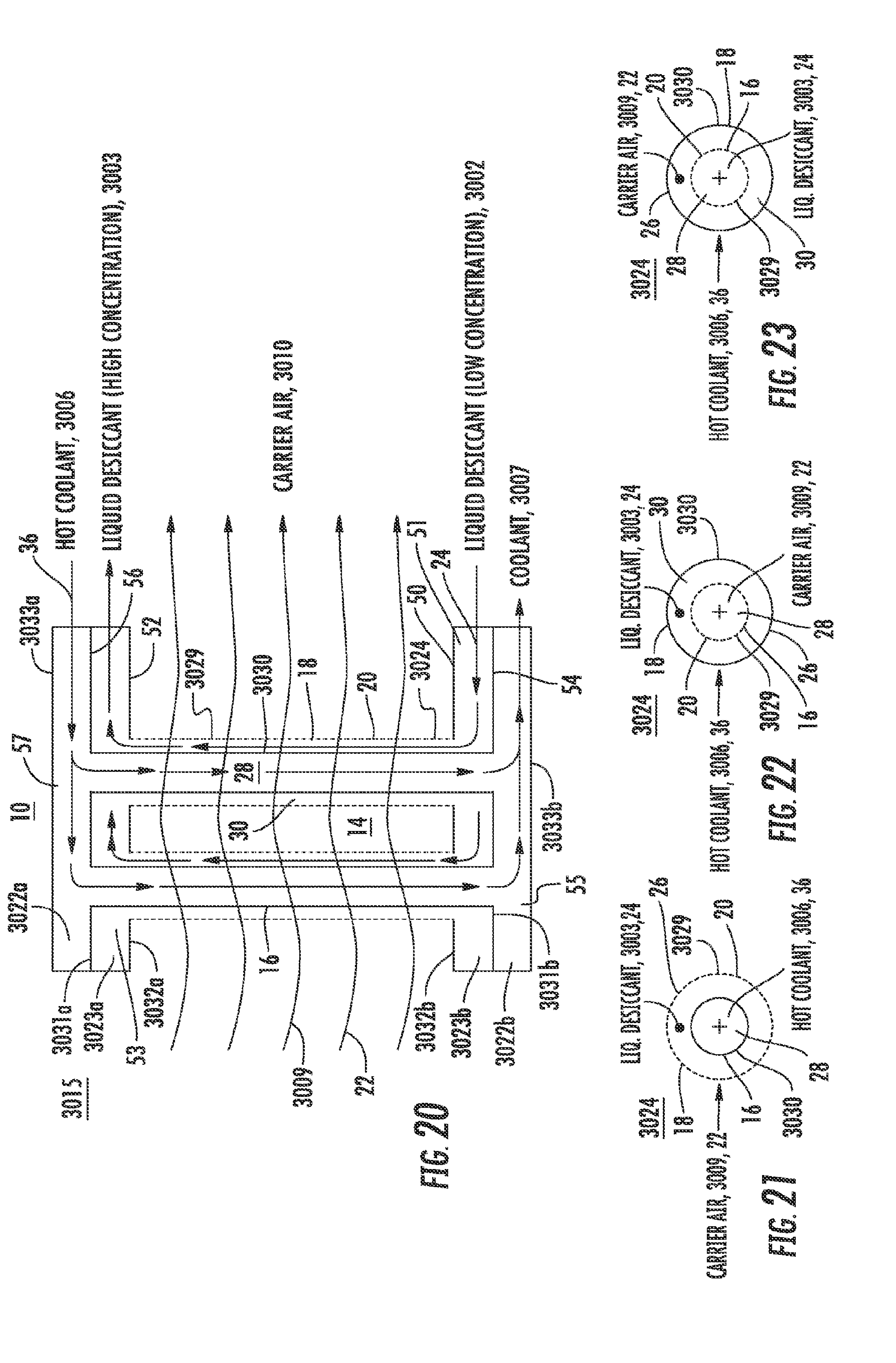


FIG. 20

FIG. 21

FIG. 22

FIG. 23

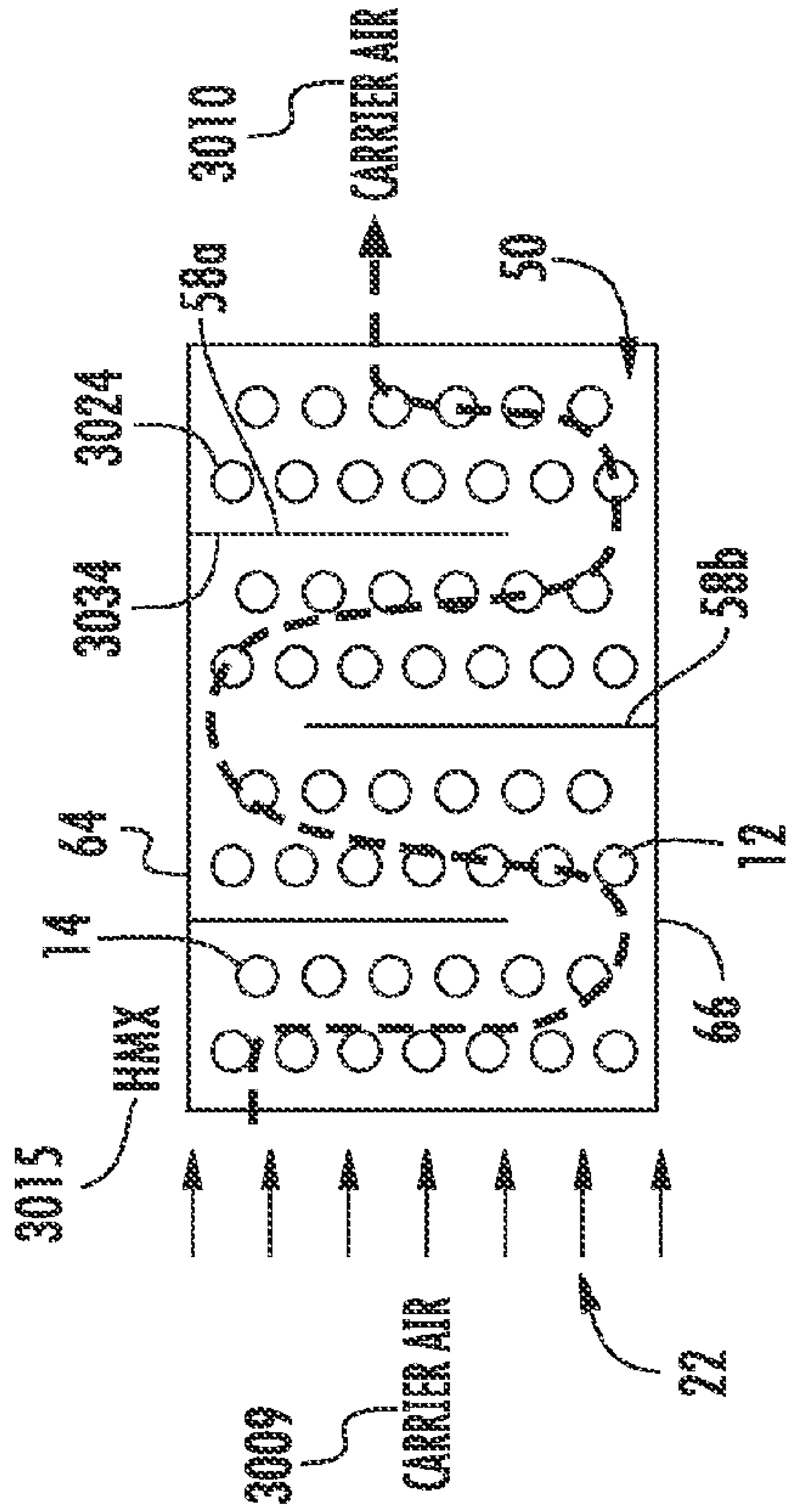


FIG. 25

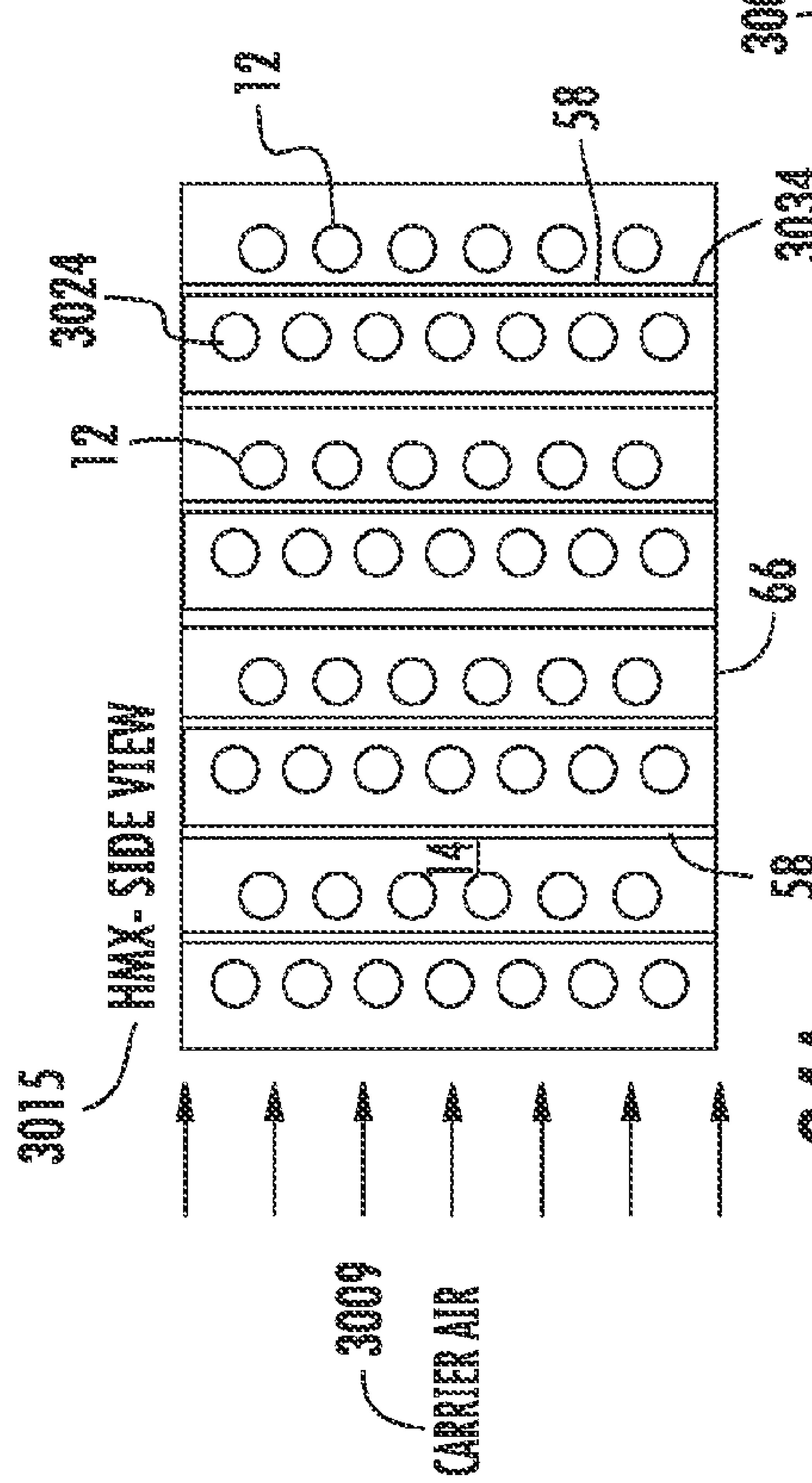


FIG. 24A

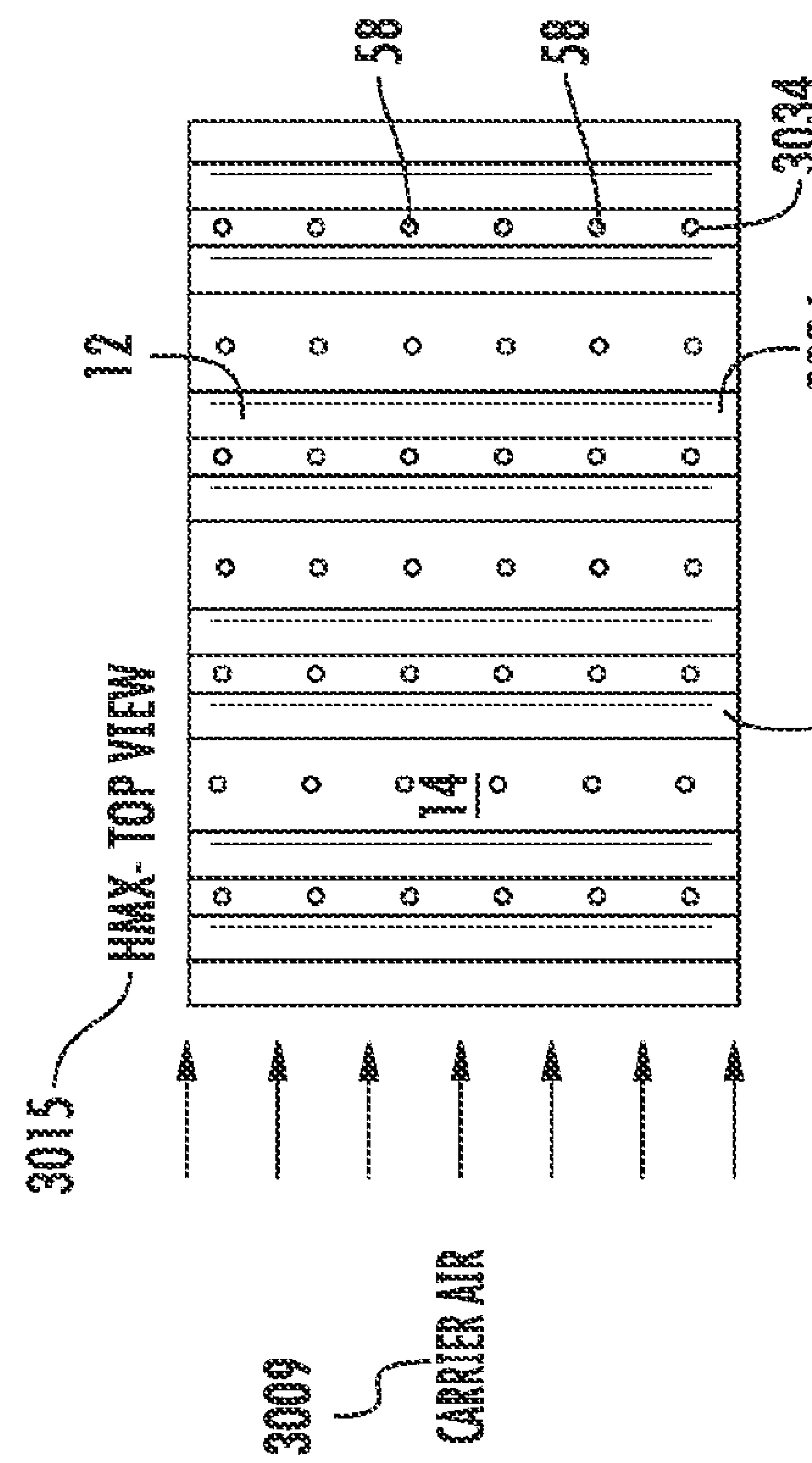
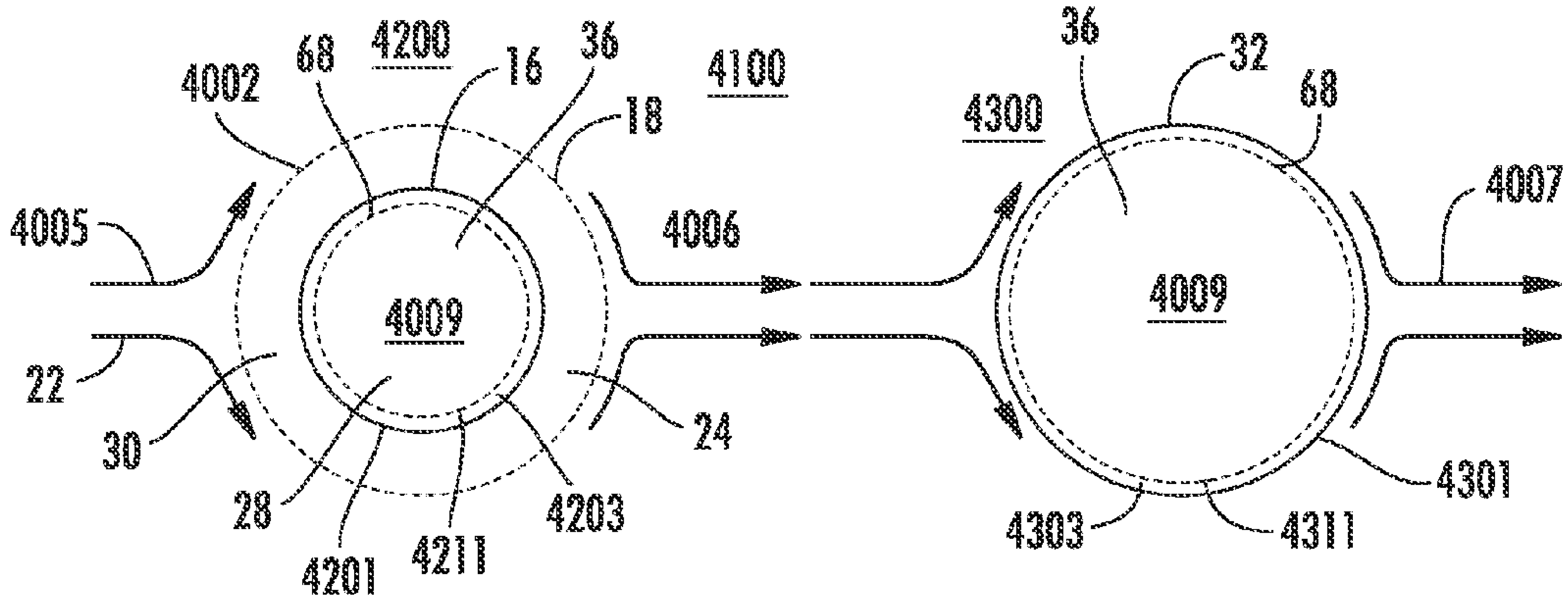
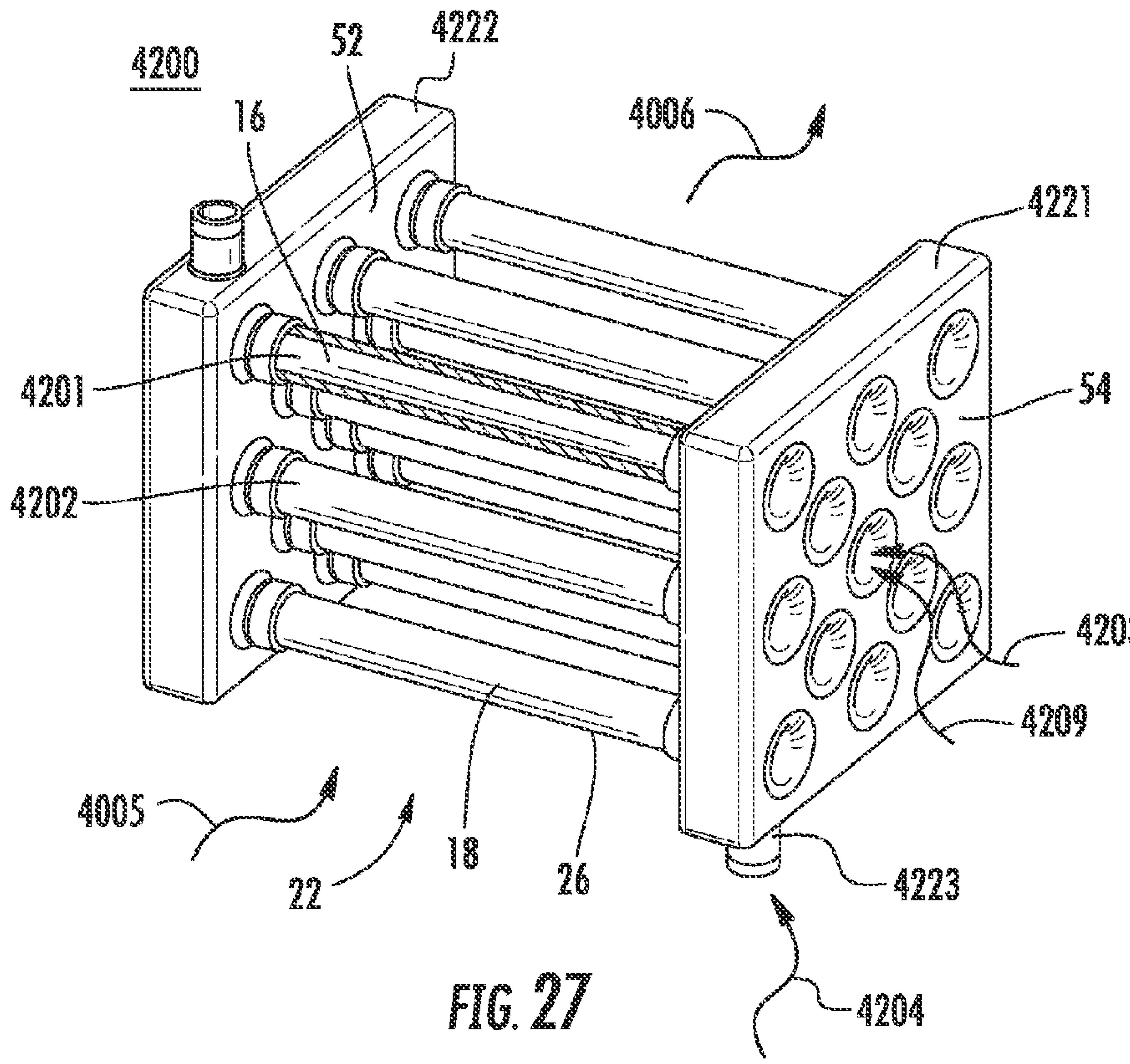


FIG. 24B



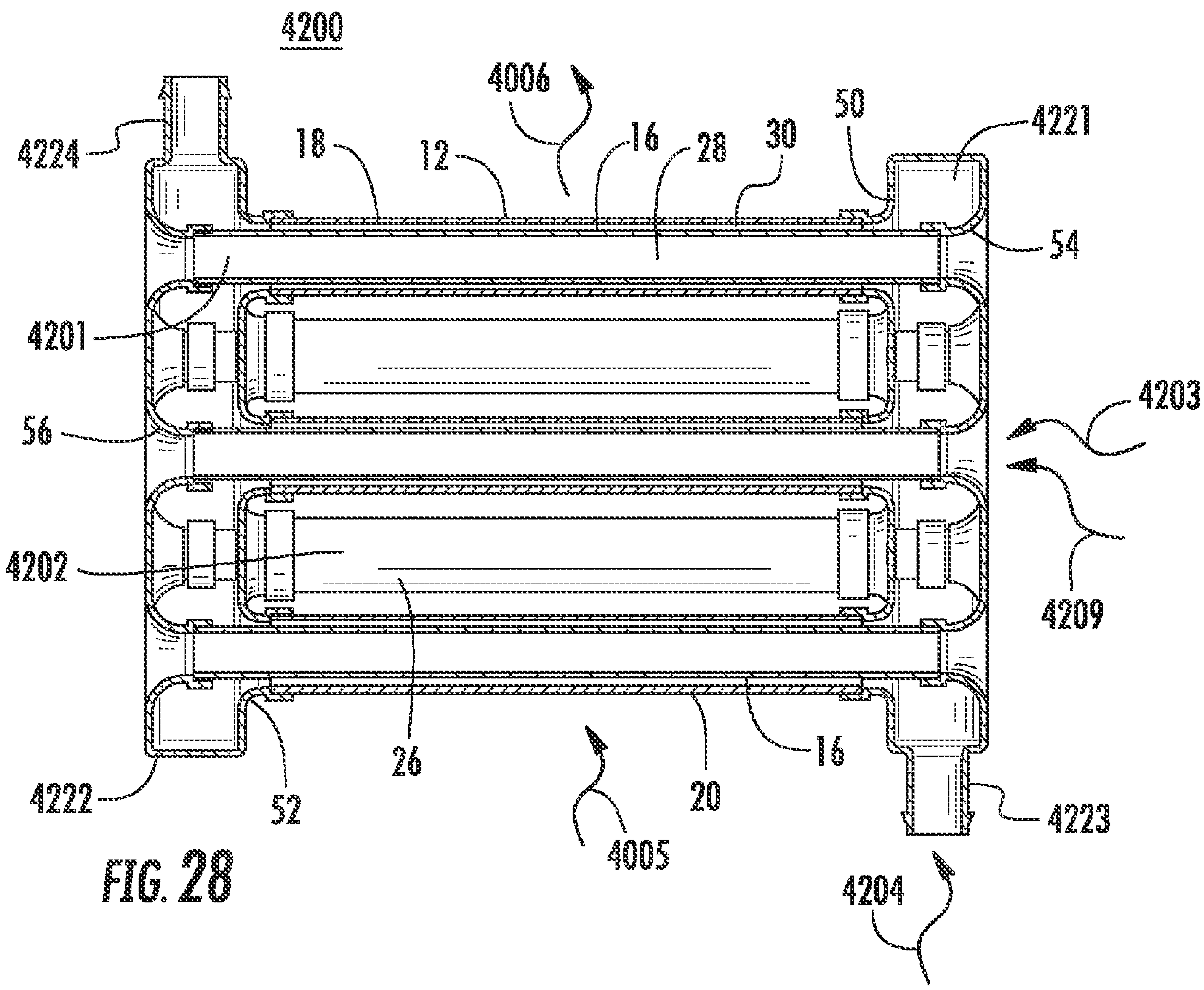
68
4200
16
36
4100
4002
18
4005
4006
4009
22
30
24
28
4201
4211
4203
36
32
4300
68
4007
4009
4301
4303
4311

FIG. 26



4200
52
4222
16
4006
4221
4201
54
4202
4203
4209
4005
22
18
26
4223
4204

FIG. 27


4200
4006
4224
18
12
16
28
30
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4221
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4201
4203
56
4202
4209
26
16
20
4222
52
4005
4223
4204

FIG. 28

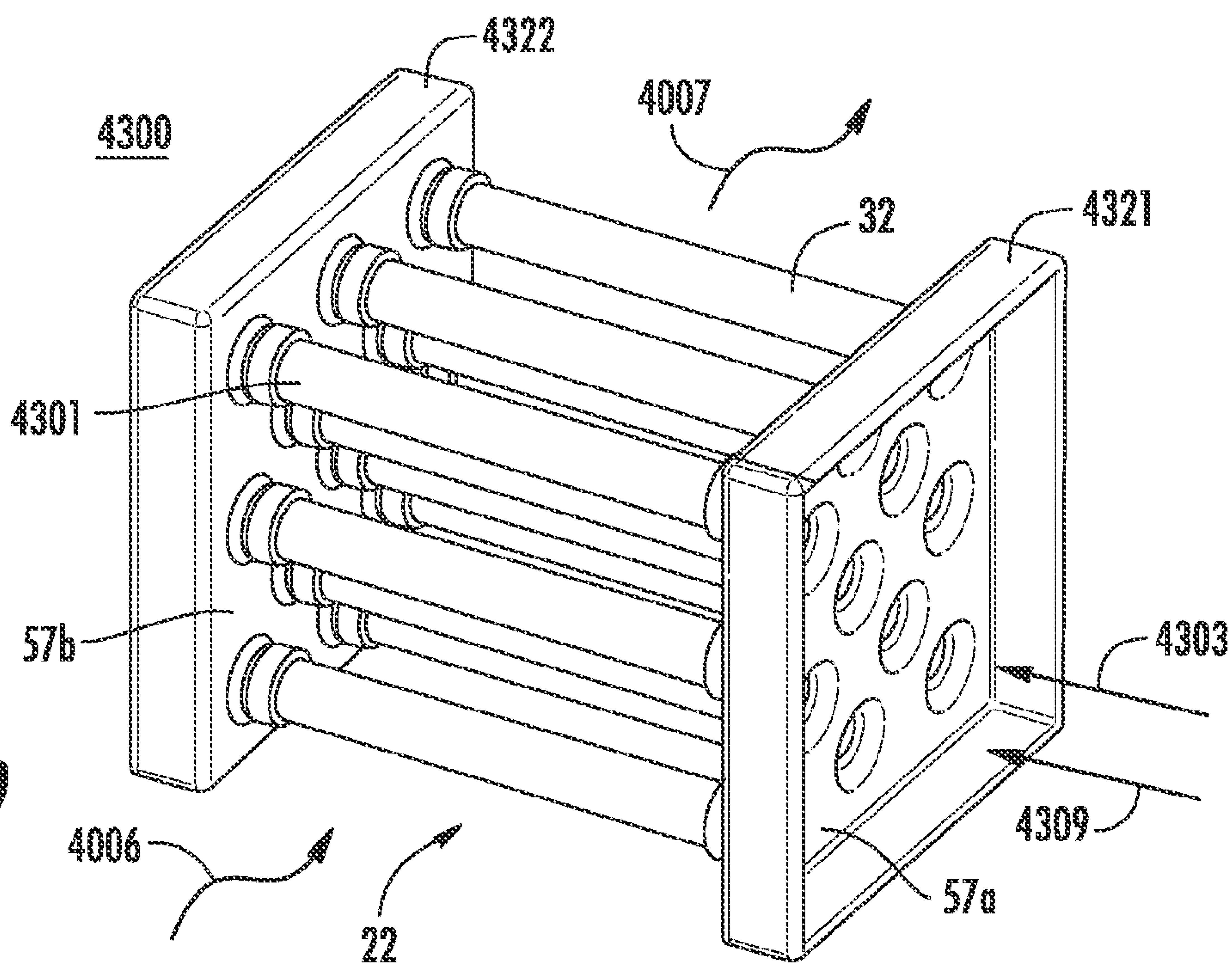

4322
4007
4300
32
4321
4301
57b
4303
4309
4006
22
57a

FIG. 29

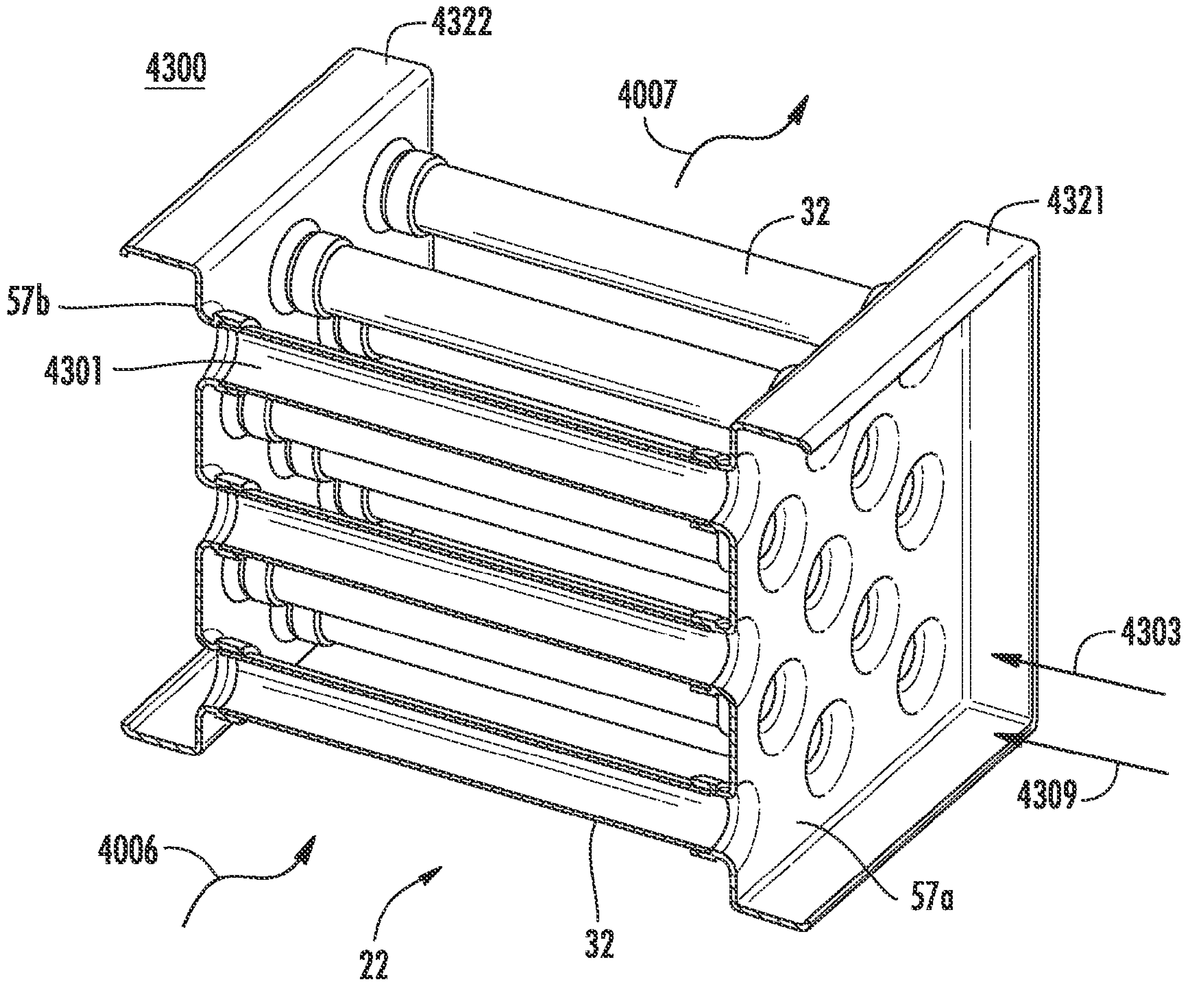


FIG. 30

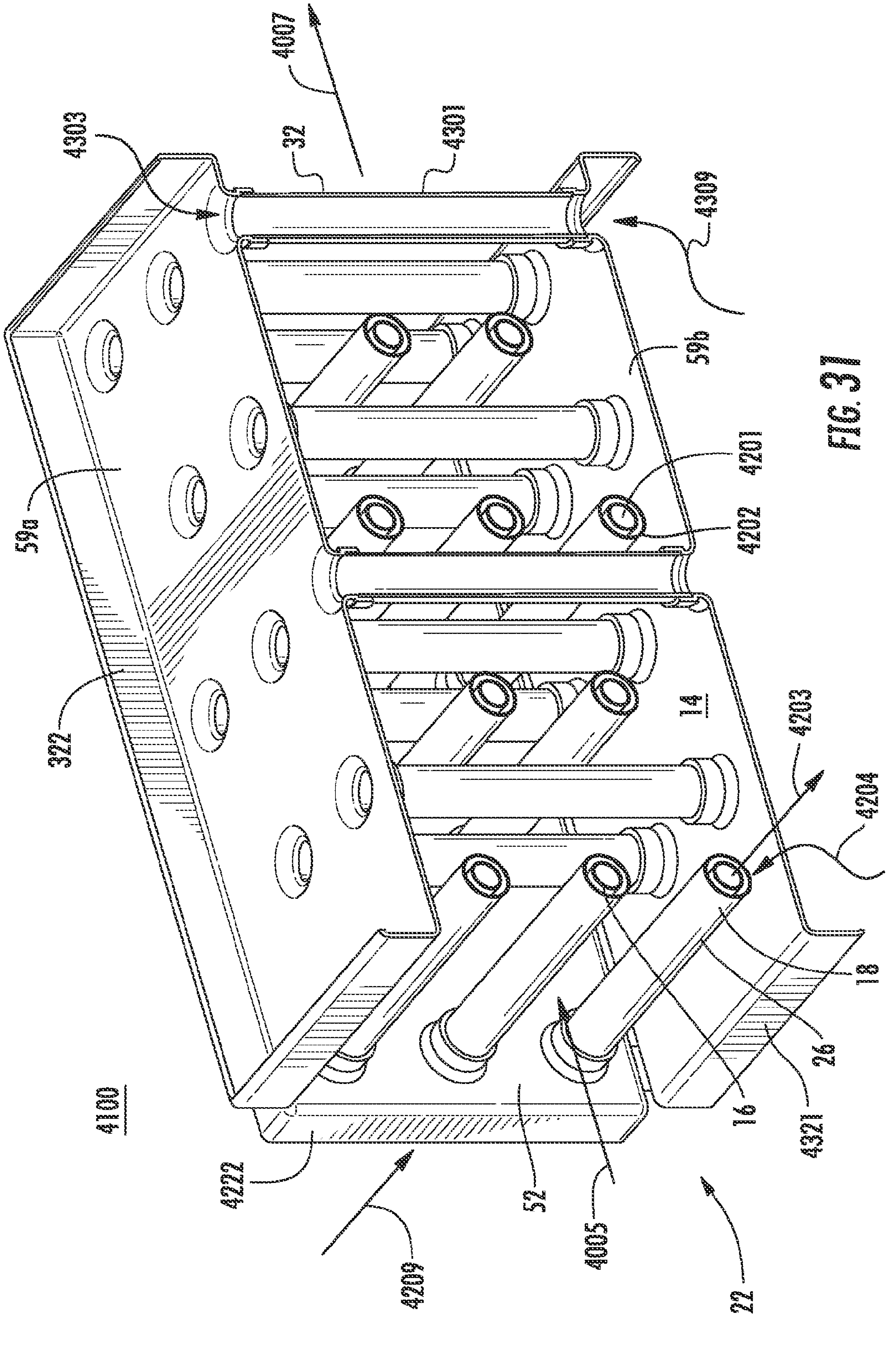
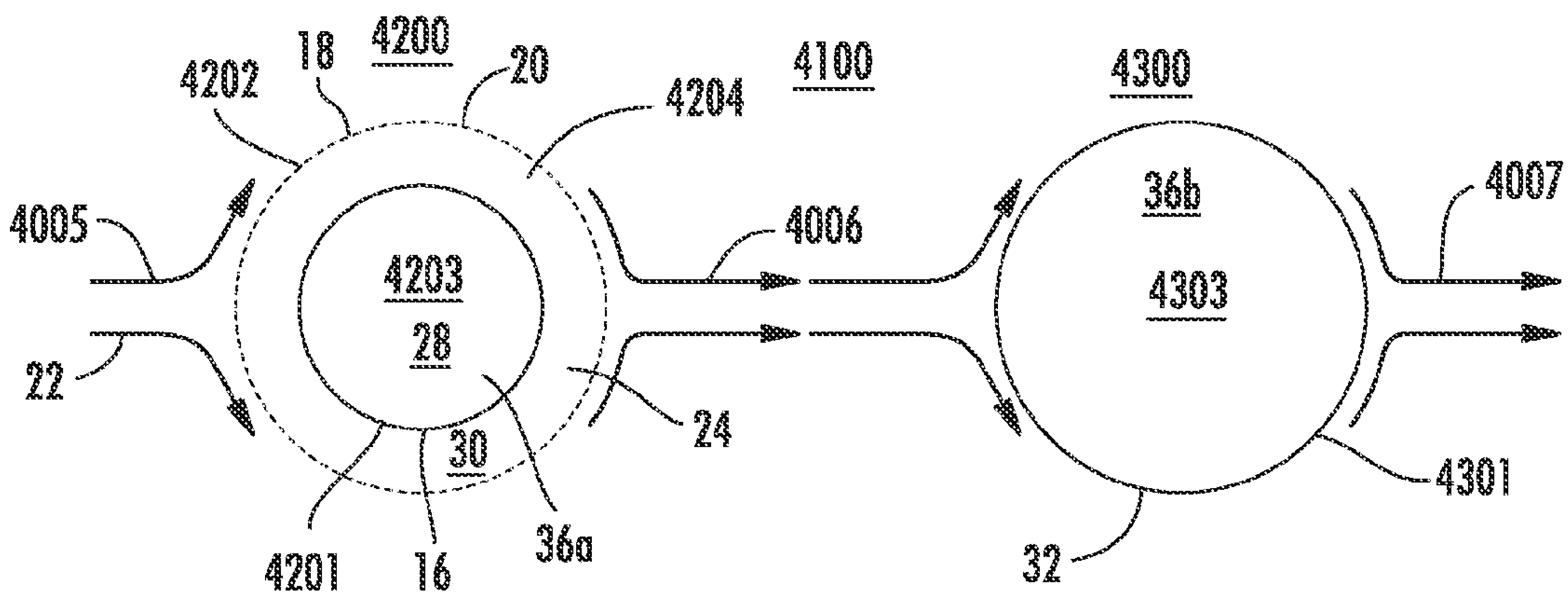
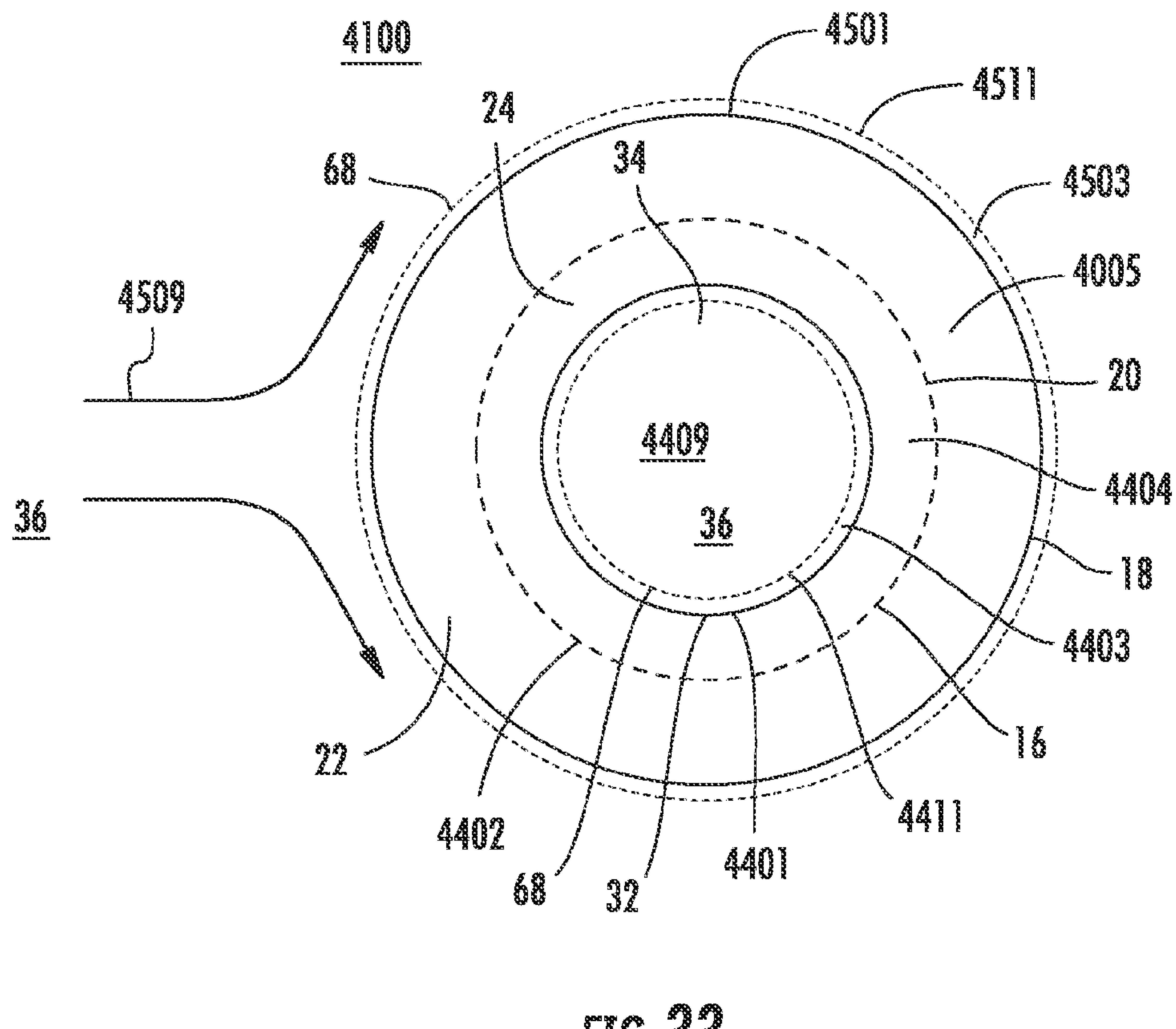

4007
4303
32
4301
4309
59b
59a
4201
4202
322
14
4203
4204
18
26
16
4321
4100
4222
52
4005
4209
22

FIG. 37



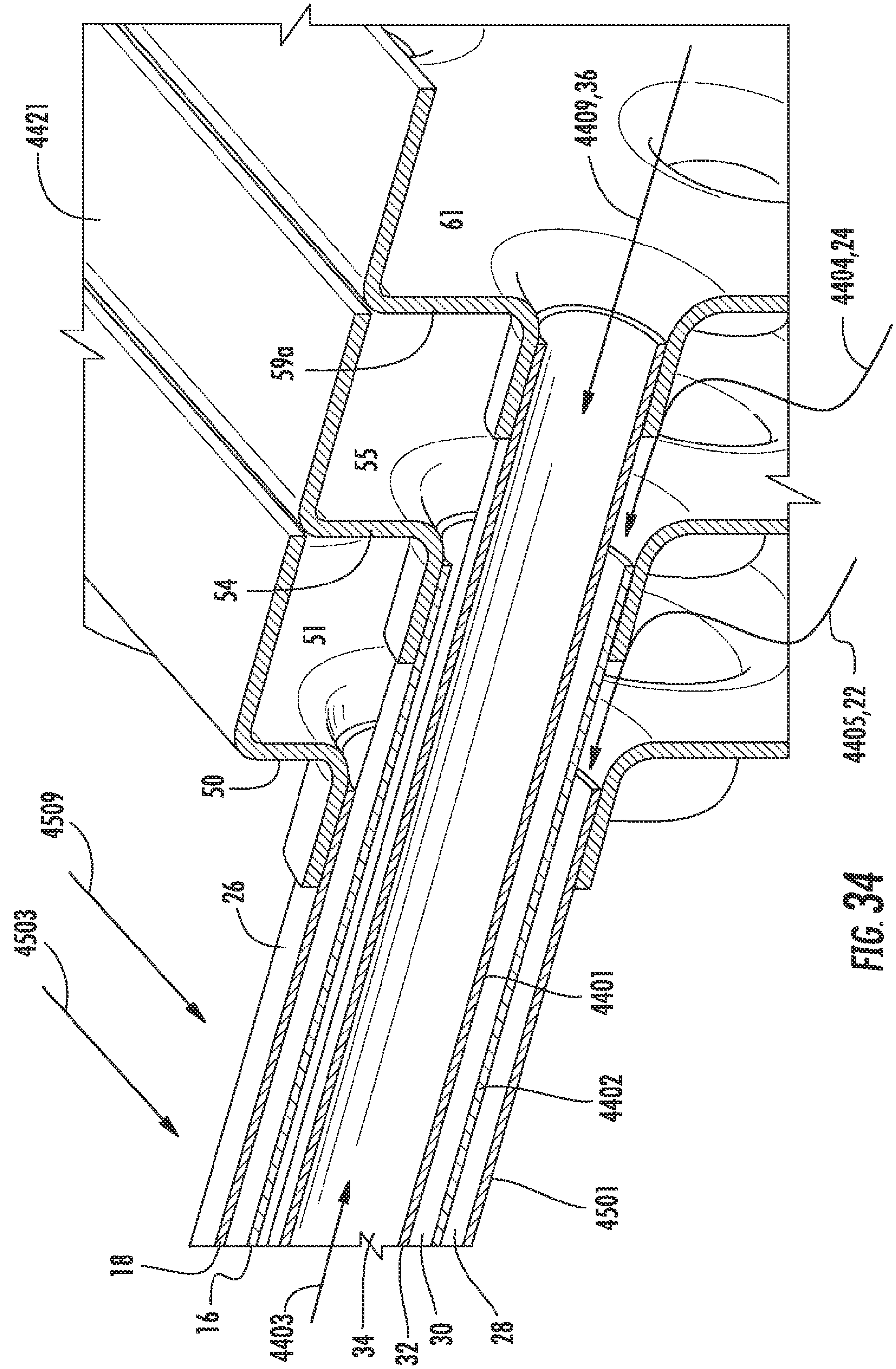
4200
18
20
4202
4204
4100
4300
36b
4005
4006
4007
4203
28
4303
22
24
30
4301
4201
16
36a
32

FIG. 32



4100
4501
4511
24
34
68
4503
4005
4509
20
4409
4404
36
36
18
4403
22
16
4402
4411
68
32
4401

FIG. 33


4421
4409,36
61
59a
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54
51
50
4404,24
4405,22
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4509
4503
4401
4402
4501
18
16
4403
34
32
30
28

FIG. 34

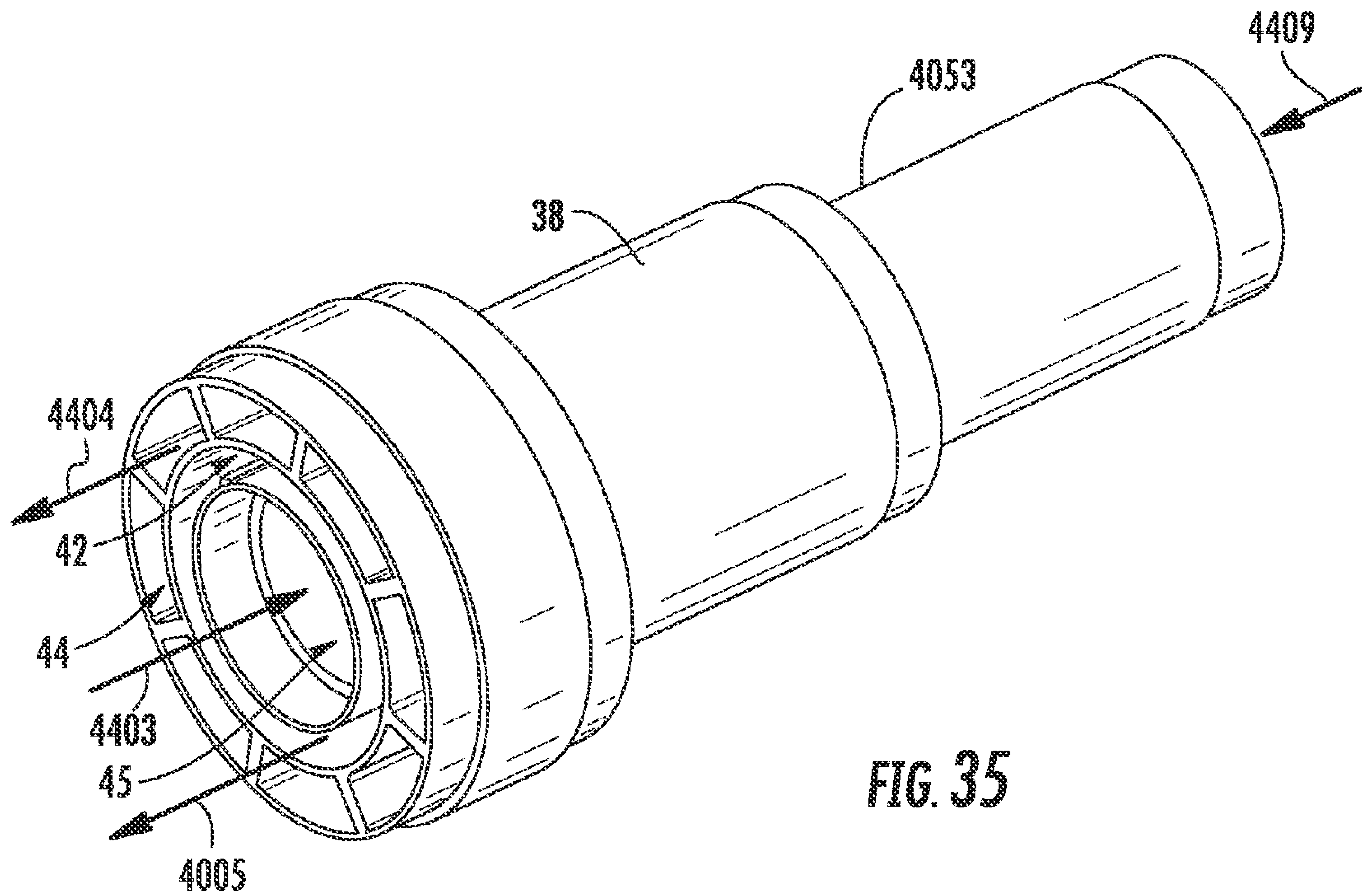

FIG. 35

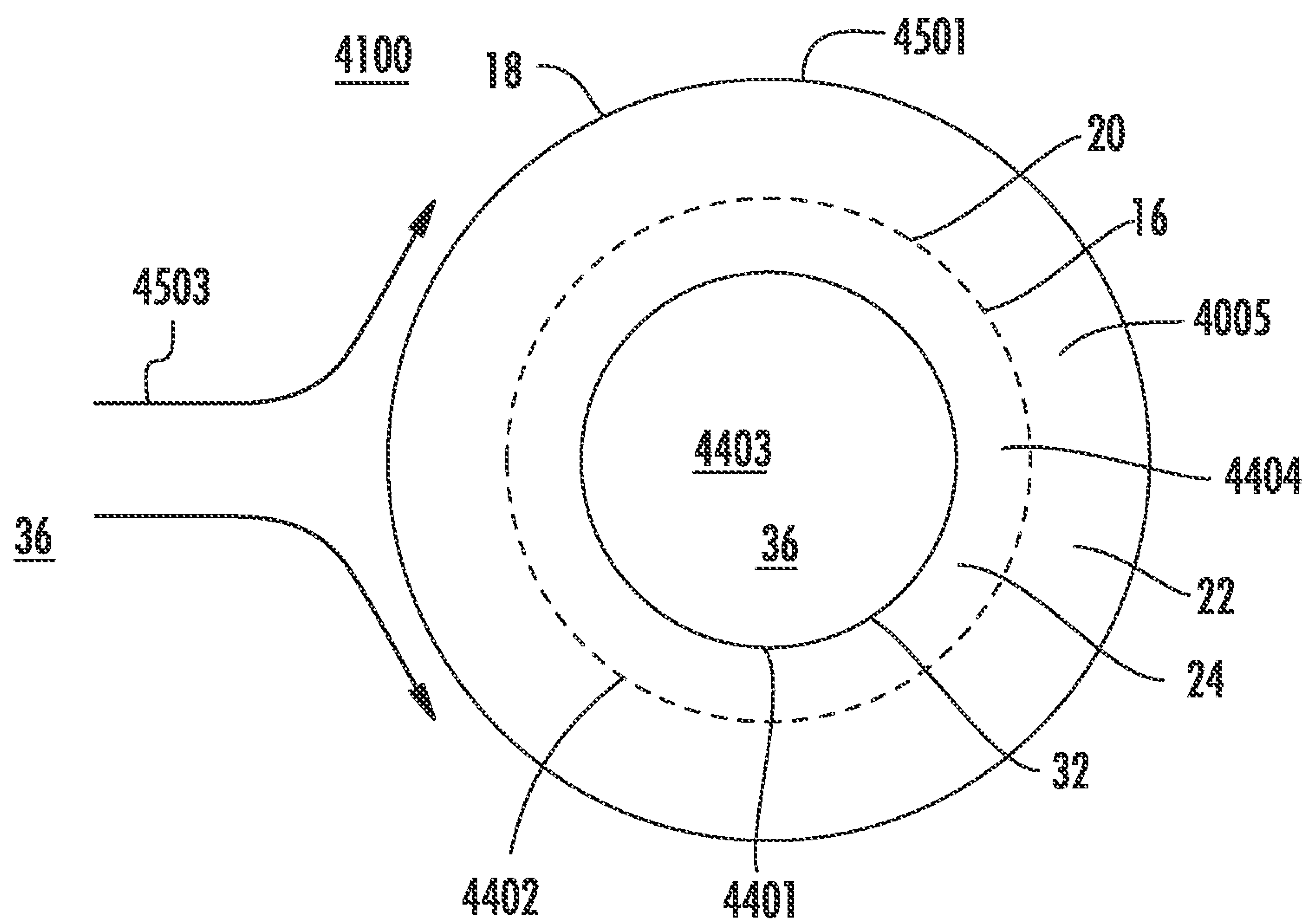
4100
18
4501
20
16
4503
4005
4403
4404
36
36
22
24
32
4402
4401

FIG. 36

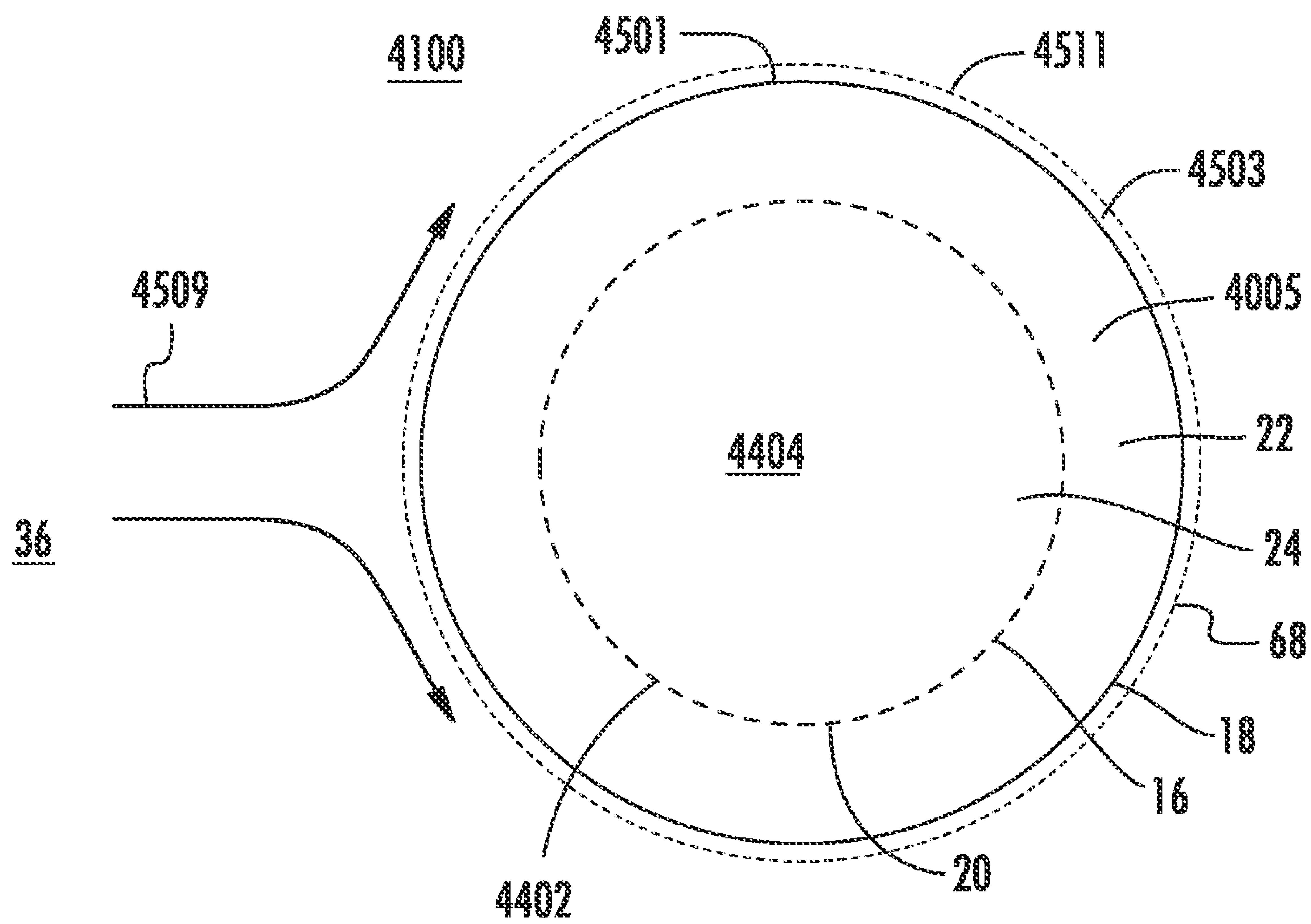
4100
4501
4511
4503
4509
4005
4404
22
36
24
68
18
16
20
4402

FIG. 37

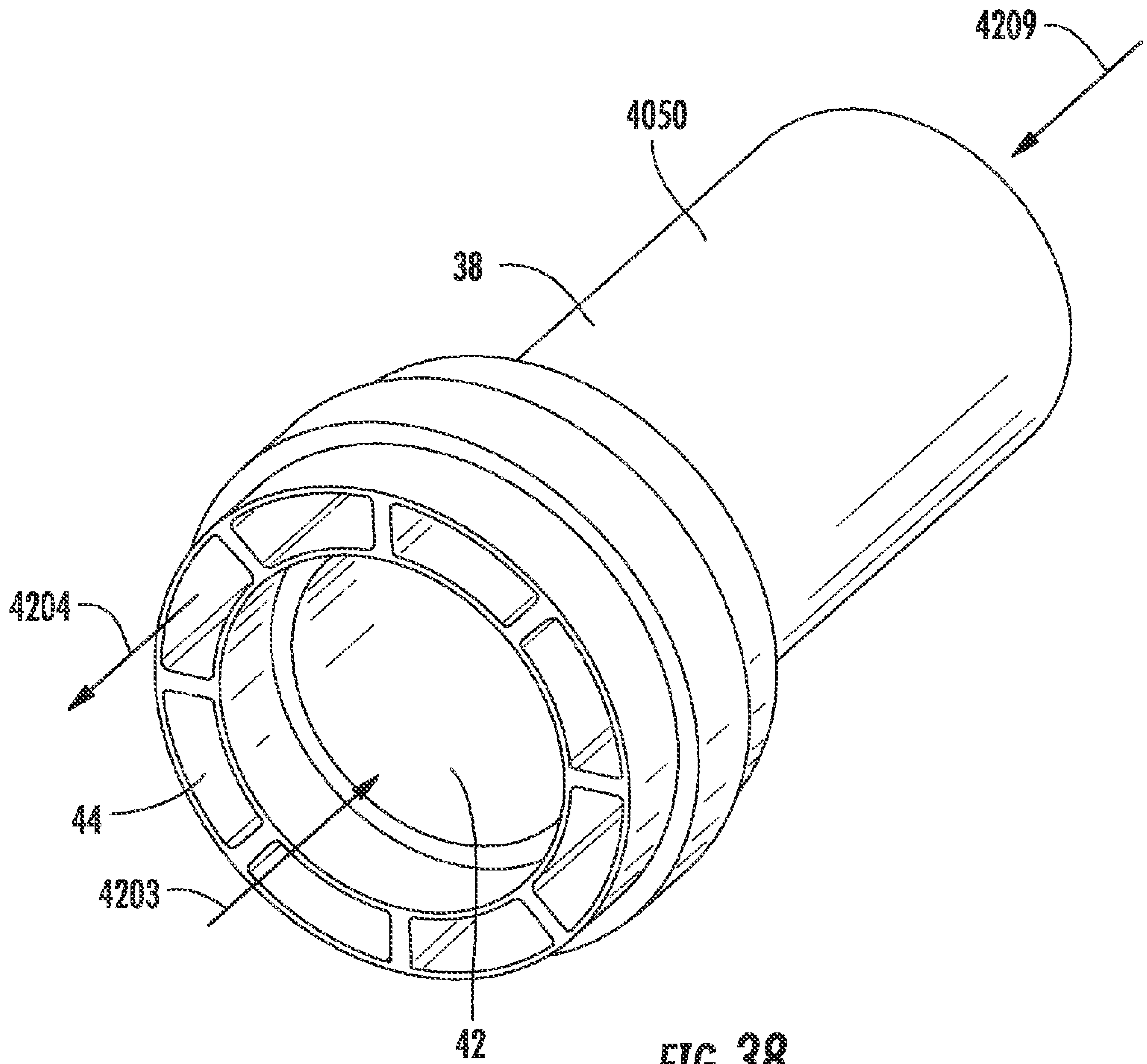

FIG. 38

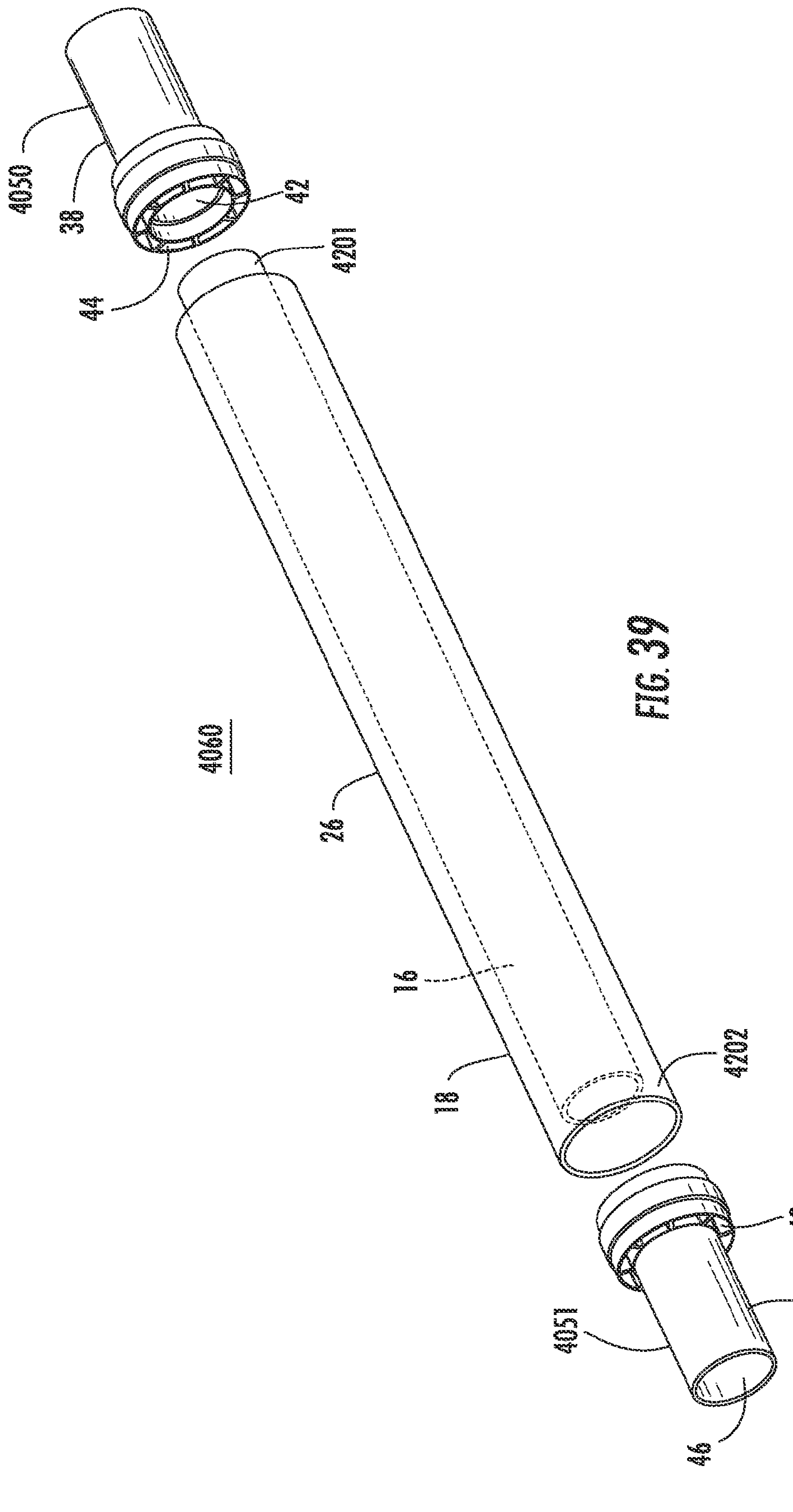

FIG. 39

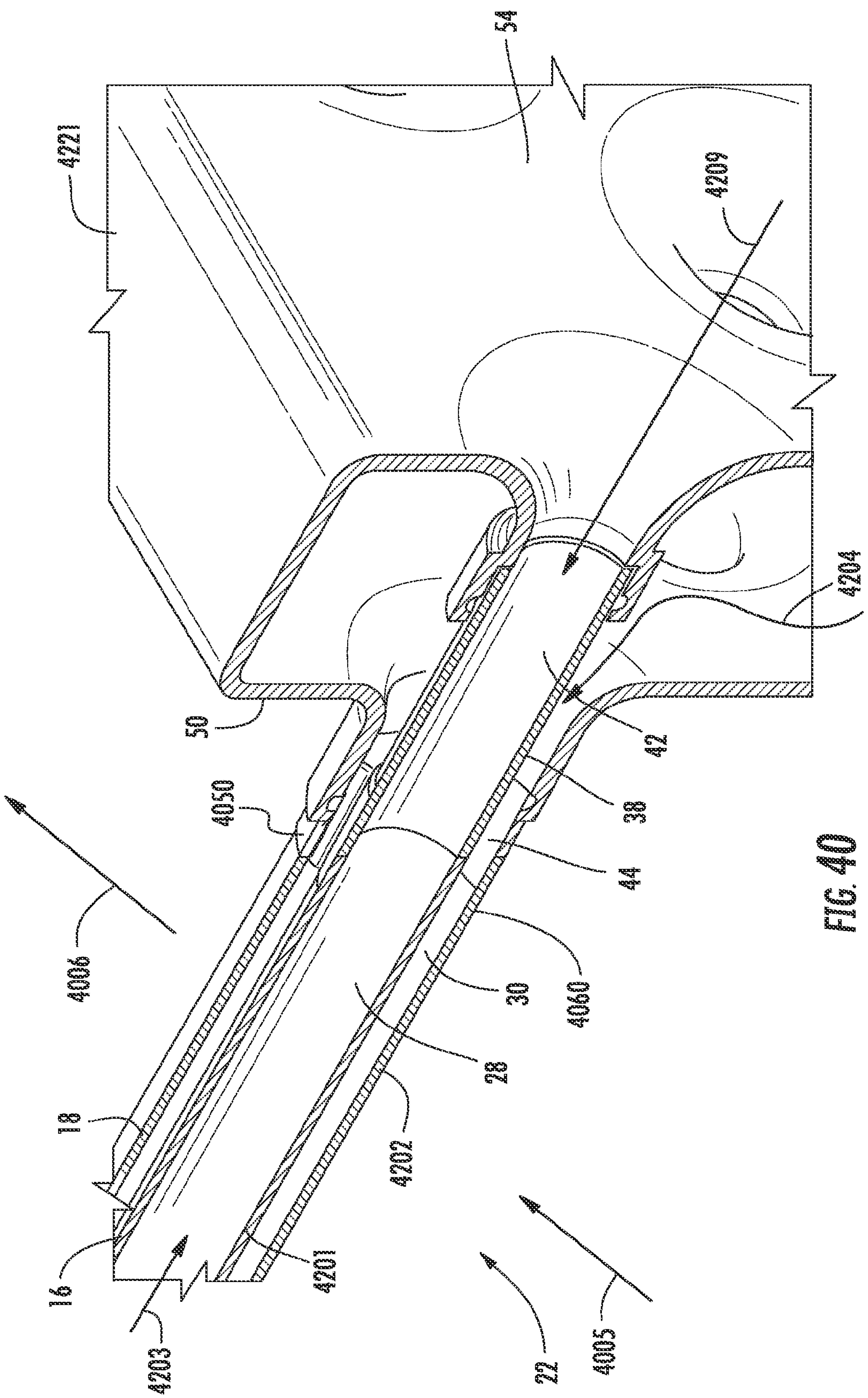
54
4221
4209
50
4204
42
38
4050
44
4006
4060
30
28
18
4202
16
4201
4203
22
4005

FIG. 40

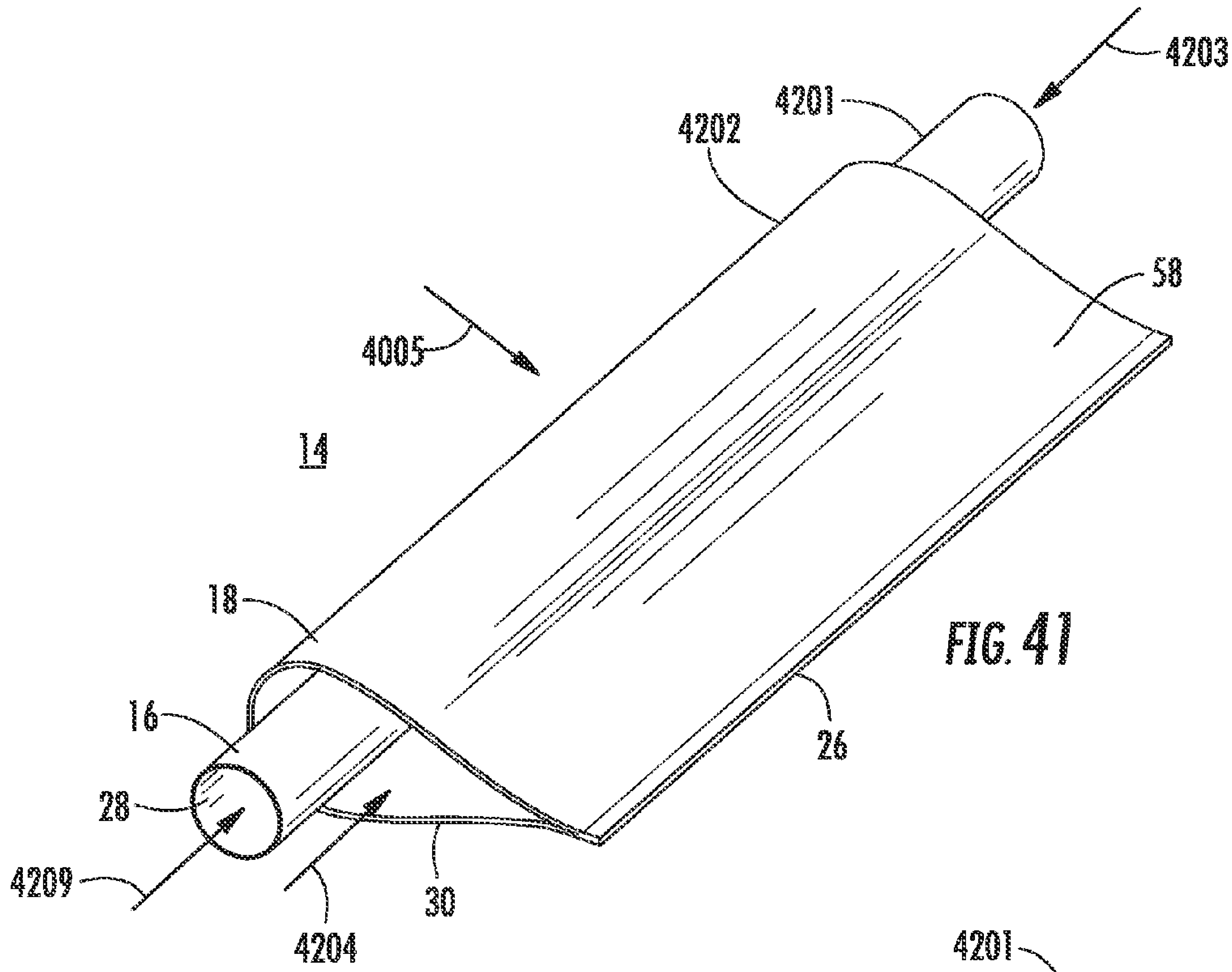

FIG. 41

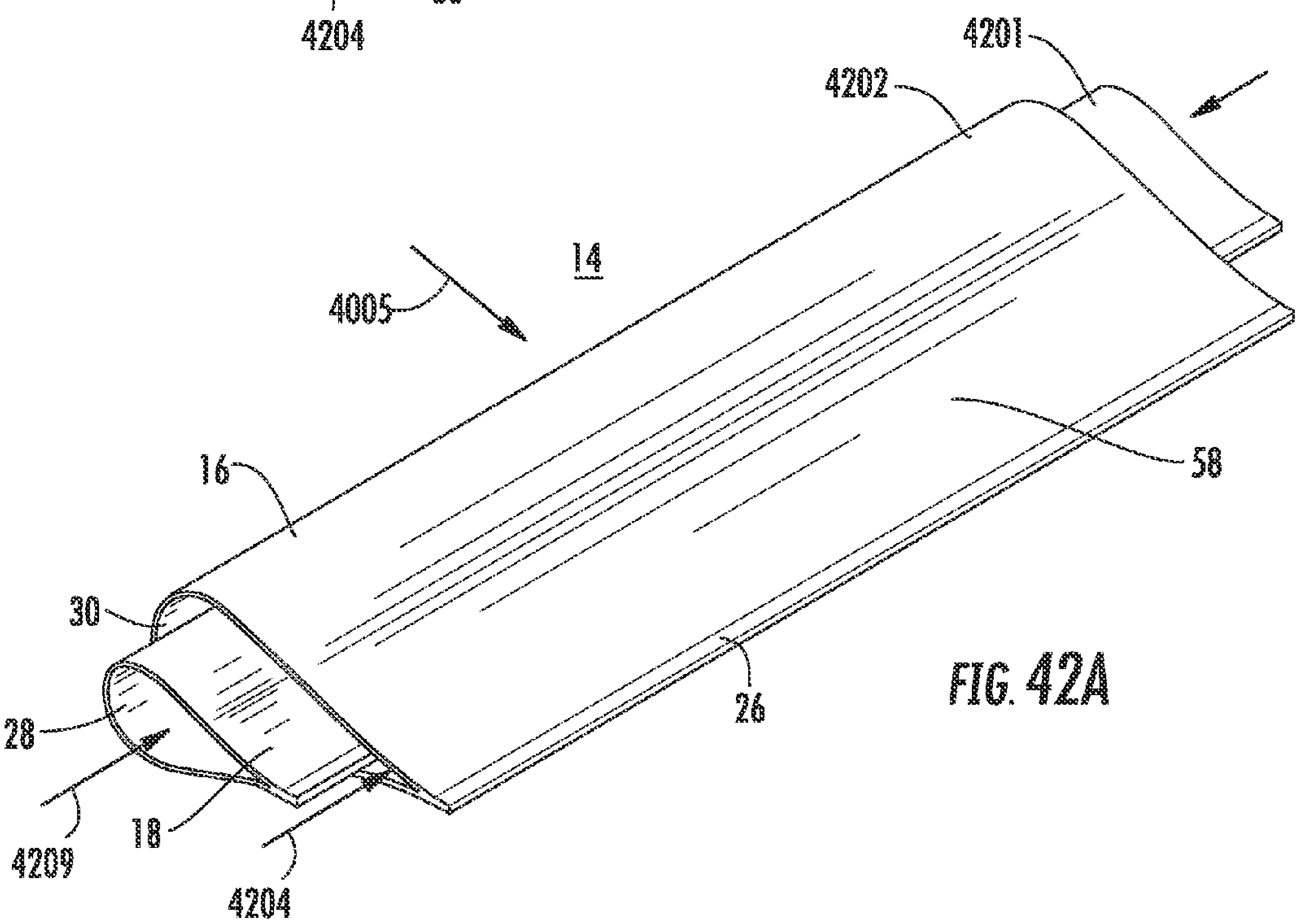

FIG. 42A

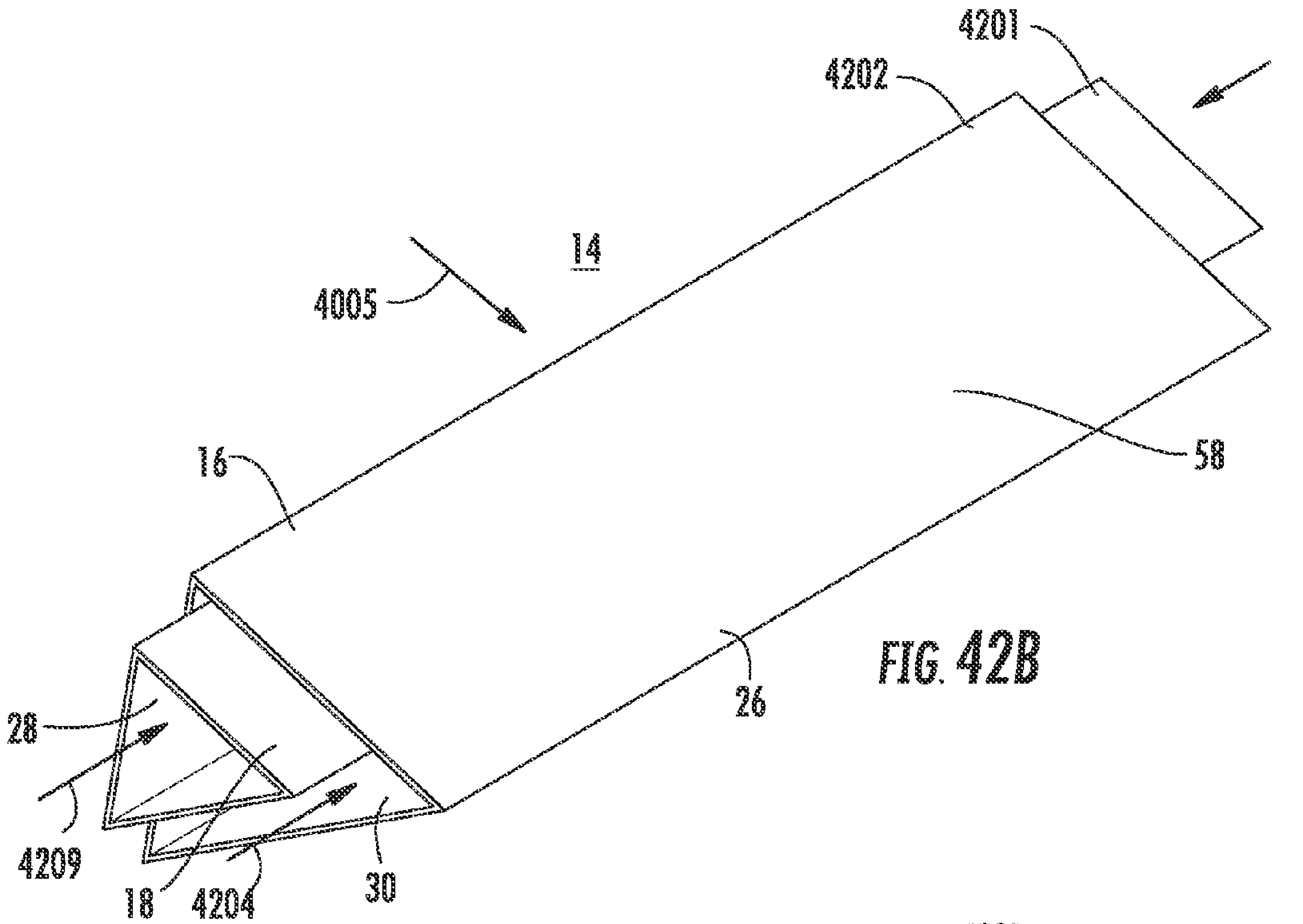

FIG. 42B

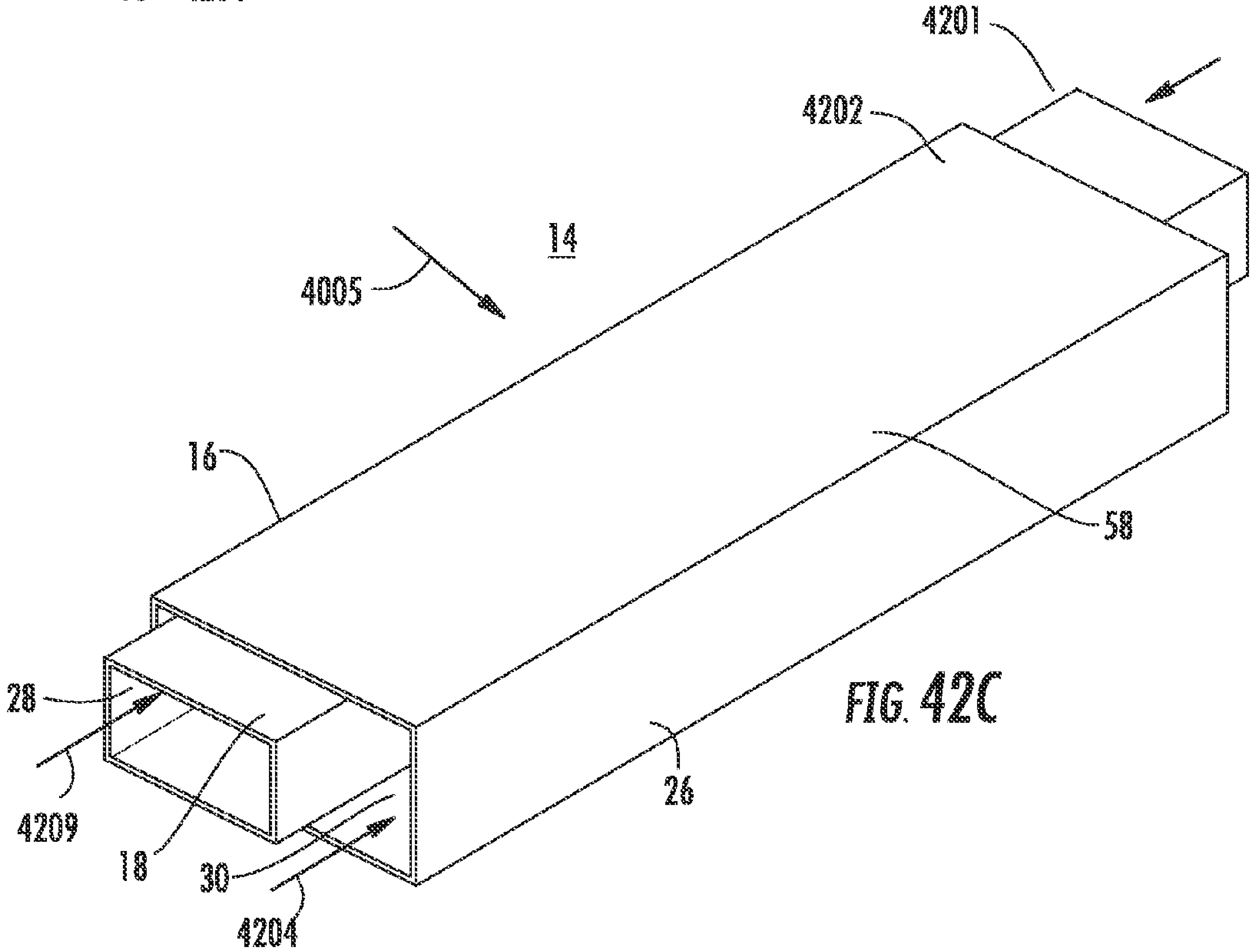

FIG. 42C

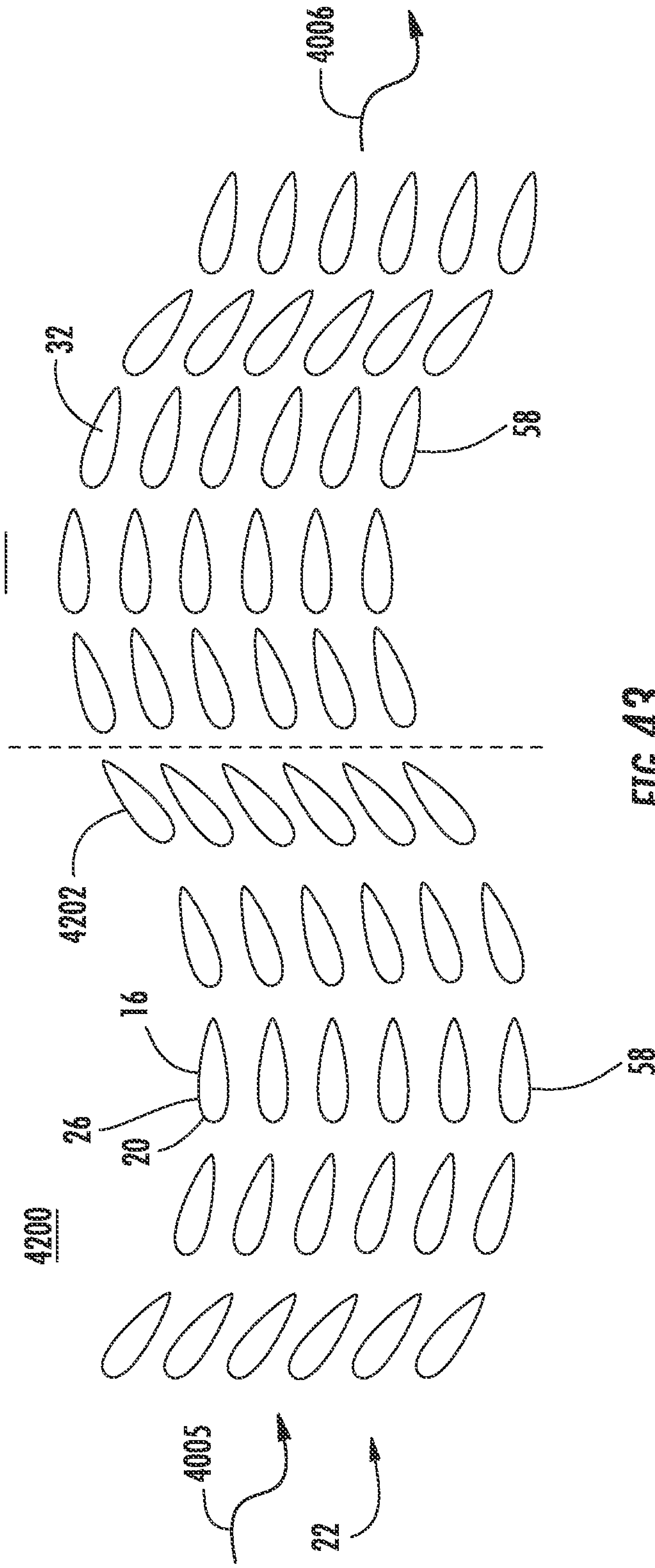

FIG. 43

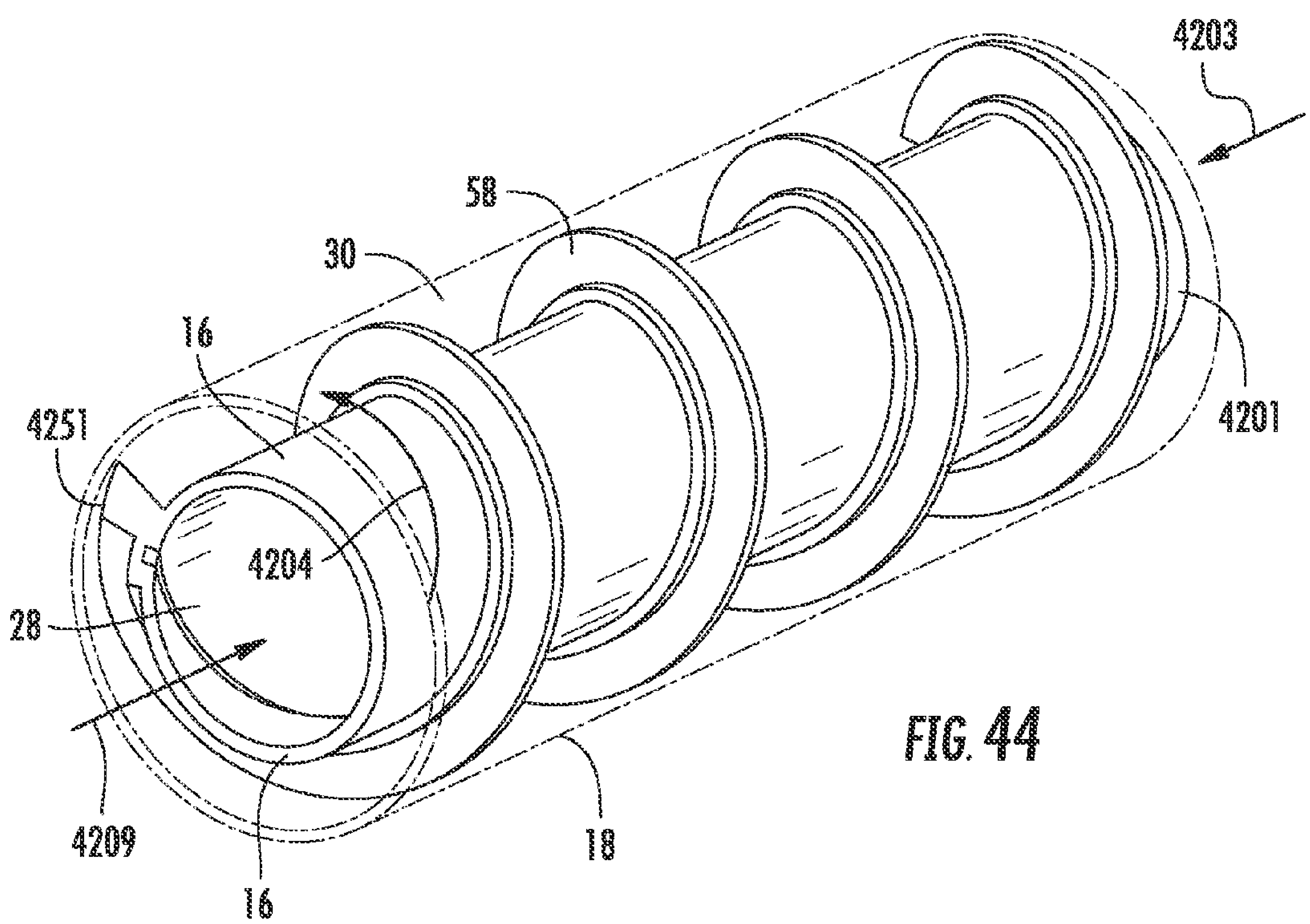

FIG. 44

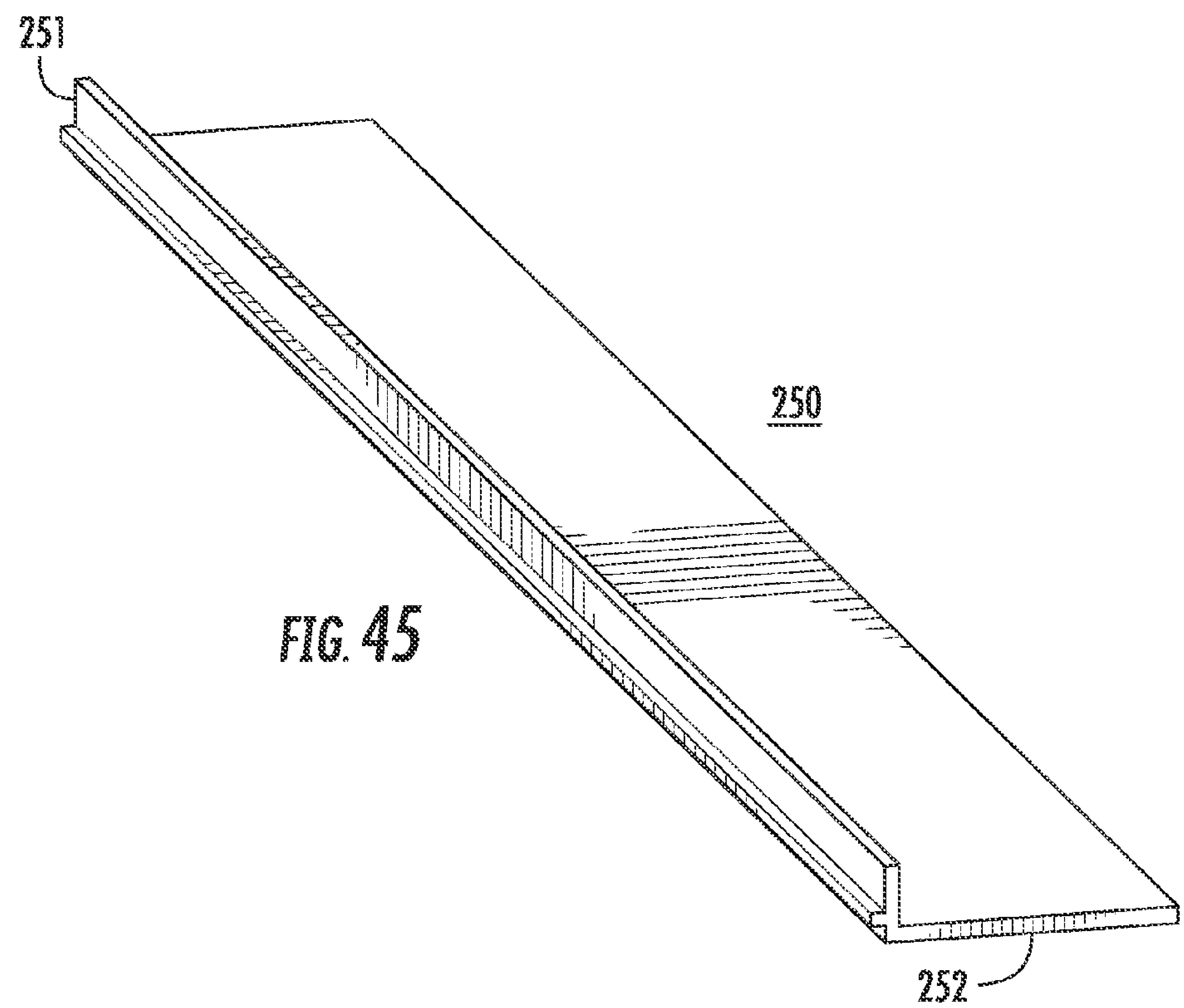

FIG. 45

HEAT AND MASS TRANSFER DEVICE AND SYSTEMS INCLUDING THE SAME

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application No. 61/940,455, filed Feb. 16, 2014; U.S. Provisional Patent Application No. 61/949,893, filed Mar. 7, 2014; U.S. Provisional Patent Application No. 61/991,198, filed May 9, 2014; U.S. Provisional Patent Application No. 62/058,476, filed Oct. 1, 2014; and U.S. Provisional Patent Application No. 62/058,479, filed Oct. 1, 2014, the entireties of which are incorporated herein by reference.

FIELD OF THE INVENTION

[0002] The present invention relates generally to the field of combined mass and heat transfer devices and systems, such as liquid desiccant air conditioning systems, that include the same.

BACKGROUND

[0003] Air conditioning refers to the heating, cooling, cleaning, humidification and dehumidification of air. The most prevalent air conditioning systems employ vapor compression cycles, in which heat is pumped from one environment to another via a refrigerant that operates under two different pressure regimes so that the temperature can be increased when heat needs to be rejected to the environment or decreased when heat is to be absorbed by the refrigerant. The pressure difference in these systems is maintained by means of a mechanical compressor. This compressor is powered using electricity. The vast majority of air conditioning systems in commercial use employ the vapor compression cycle.

[0004] The principal limitation to the vapor compression cycle is that it is for all intents and purposes a sensible heat rejection device with minor capabilities to address the latent heat needs of a building. This is because the vapor compression cycle is only able to change the temperature of the air. Given this, the prevalent manner in which vapor compression air conditioning systems address the latent heat of a building is by reducing the temperature of the air to a point below its dew point and by removing water through condensation. In most cases, the air must be reheated in order to arrive at the desired building supply air temperature. This process is energy intensive.

[0005] Methods for dehumidification of the air conditioning incoming air have been invented and proposed. Among these is the use of a liquid desiccant loop coupled with an evaporative cooling system to generate cooling and dehumidification without requiring cooling the air to the dew point. These systems are designed using a plate heat and mass transfer arrangement in which liquid desiccant flows within selectively water permeable membranes that are attached to fiat plates. The liquid desiccant flow absorbs moisture from air being dehumidified and then transfers it to a separate air stream that absorbs this moisture from the liquid desiccant. The air being dehumidified drops in temperature, cooling the air being dehumidified. Multiple plates stacked together form the heat and mass transfer device.

[0006] The plate arrangement has advantages in that it allows for a single device that does both air cooling and dehumidification using liquid desiccant streams. An example of this is described in US Patent Application, US 20100319370A1, titled "indirect evaporative cooler using membrane-contained liquid desiccant for dehumidification."

SUMMARY

[0007] A heat and mass exchanger system is described. The heat and mass exchange system can include a plurality of exchange components extending across a heat and mass exchanger (HMX) duct, where a flow through the HMX duct is cross-flow relative to said exchange components. The exchange components can include a plurality of first elongated, hollow conduits and a plurality of second elongated, hollow conduit, where either the first elongated, hollow conduits or the second elongated, hollow conduits have water vapor permeable exterior walls, and a carrier air stream and a liquid desiccant stream flow in contact with opposite sides of the water vapor permeable exterior walls.

[0008] These and other features, objects and advantages of the present invention will become more apparent to one skilled in the art from the following description and claims when read in light of the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIG. **1**A is a perspective view of a heat and mass transfer device as described herein, while FIG. **1**B is a cross-sectional view of the heat and mass transfer device of FIG. **19**A.

[0010] FIG. **2** is a perspective view of a tube-in-tube heat and mass transfer device as described herein.

[0011] FIG. **3** is a cross-sectional view of a mass transfer tube as described herein.

[0012] FIG. **4** is a perspective view of multiple filtration tubes housed in a larger cylindrical vessel for removal of solids from water at elevated pressures.

[0013] FIG. **5** is a perspective view of a porous support material that can be used for forming amass support conduit.

[0014] FIG. **6** is a perspective, semi-transparent view of an air conditioning process using two heat and mass exchange stages, which may be separate units or a single, combined unit.

[0015] FIG. **7** is a perspective, semi-transparent view of an air conditioning process using two heat and mass exchange stages, which may be separate units or a single, combined unit.

[0016] FIG. **8** is a perspective, semi-transparent view of an air conditioning process using two heat and mass exchange stages, which may be separate units or a single, combined unit.

[0017] FIG. **9** is a perspective, semi-transparent view of an air conditioning process using two heat and mass exchange stages, which may be separate units or a single, combined unit.

[0018] FIG. **10** is a diagram of a liquid desiccant regeneration and dehumidification system as described herein.

[0019] FIG. **11** is a diagram of a liquid desiccant regeneration and dehumidification system as described herein.

[0020] FIG. **12** is a diagram of a liquid desiccant generation and dehumidification system as described herein.

[0021] FIG. **13** is a diagram of a liquid desiccant regeneration and dehumidification system as described herein.

[0022] FIG. **14** is a diagram of a liquid desiccant regeneration and dehumidification system described herein.

[0023] FIG. **15** is a diagram of a misting device as disclosed herein.

[0024] FIG. **16** is a diagram of a liquid desiccant regeneration system as described herein.

[0025] FIG. **17** is a diagram of a liquid desiccant regeneration system as described herein.

[0026] FIG. **18** is a perspective view of a heat and mass exchange stage as described herein.

[0027] FIG. **19** is a perspective view of a heat and mass exchange stage as described herein.

[0028] FIG. **20** is a cross-sectional view showing the flow pattern of fluid through a heat and mass exchange stage as described herein.

[0029] FIG. **21** is a cross-sectional view of a tube-in-tube assembly as described herein.

[0030] FIG. **22** is a cross-sectional view of a tube-in-tube assembly as described herein.

[0031] FIG. **23** is a cross-sectional view of a tube-in-tube assembly as described herein.

[0032] FIG. **24**A is a side or top view of a heat and mass exchange assembly, including flow disruptors, as described herein, while FIG. **24**B is a top or side view of the same heat and mass exchange assembly.

[0033] FIG. **25** is a side or top view of a heat and mass exchange assembly, including flow disruptors, as described herein.

[0034] FIG. **26** a cross-sectional view of the arrangement of heat and mass transfer tubes in a heat and mass transfer device as described herein.

[0035] FIG. **27** is a perspective view of a heat and mass transfer device adapted for dehumidification as described herein.

[0036] FIG. **28** is a cross sectional view of the heat and mass transfer device of FIG. **27**.

[0037] FIG. **29** is a perspective view of a cooling stage as described herein.

[0038] FIG. **30** is a cross-sectional, perspective view of the cooling stage of FIG. **29**.

[0039] FIG. **31** is a heat and mass transfer device that combines dehumidification and cooling as described herein.

[0040] FIG. **32** a cross-sectional view of the arrangement of heat and mass transfer tubes in a heat and mass transfer device as described herein.

[0041] FIG. **33** a lateral cross-sectional view of a tube-in-tube-in-tube arrangement of heat and mass transfer tubes in a heat and mass transfer device as described herein.

[0042] FIG. **34** is a longitudinal cross-sectional view of a tube-in-tube-in-tube arrangement of heat and mass transfer tubes and their relation to the manifolds for each flow channel as described herein.

[0043] FIG. **35** is an end cap or coupling device for constructing tube-in-tube-in-tube components and sealing them to mounting manifolds as described herein.

[0044] FIG. **36** a lateral cross-sectional view of a tube-in-tube-in-tube arrangement of heat and mass transfer tubes in a heat and mass transfer device as described herein.

[0045] FIG. **37** is a lateral cross-section of a tube-in-tube arrangement that include a hydrophilic surface for enhanced heat transfer (e.g., cooling) as described herein.

[0046] FIG. **38** is an end cap or coupling device for constructing tube-in-tube components and sealing them to mounting manifolds as described herein.

[0047] FIG. **39** is an exploded view of a tube-in-tube component as described herein.

[0048] FIG. **40** is a longitudinal cross-sectional view of a tube-in-tube arrangement of heat and mass transfer tubes and their relation to the manifolds for each flow channel as described herein.

[0049] FIG. **41** is a perspective view of a tube-in-tube arrangement as described herein, where the outer tube has the shape of an airfoil.

[0050] FIG. **42**A is a perspective view of a tube-in-tube arrangement where the inner and outer tubes have the shape of an airfoil, while the inner and outer tubes in FIG. **42**B have a triangular shape, and the inner and outer tubes in FIG. **42**C have a square or triangular shape, any of which may be helpful for elongating the flow path or inducing turbulence in a fluid (e.g., supply/process air **4005**) passing across over them.

[0051] FIG. **43** is a side view of a plurality of mass and heat transfer tubes having an airfoil shape.

[0052] FIG. **44** shows a semi-transparent view of a tube-in-tube component where the inner tube includes a flow disruptor for increasing the flow path distance of a fluid flowing through the outer channel.

[0053] FIG. **45** shows a sheet of material that can be rolled in a helical pattern to form the inner tube of FIG. **44**.

DETAILED DESCRIPTION

[0054] As shown in FIGS. **1-45**, a heat and mass exchange (HMX) device is disclosed. The HMX device is particularly adapted for high efficiency mass exchange processes. For example, where the process is drawn to dehumidification of an air stream, the heat exchange element can cool the air stream, the receiving stream (e.g., high concentration liquid desiccant stream), or both in order to enhance dehumidification. On the other end of the spectrum, a low concentration liquid desiccant stream can be heated in order to enhance dewatering of the low concentration liquid desiccant stream. Other uses for the HMX devices described herein will be apparent from the description herein.

[0055] As used herein, "conduit" and "duct" have their standard meanings and includes hollow solids, including pipes, tubes, rectangular solids, and other structures that a fluid can flow through.

[0056] As used herein, "contact" has its standard meaning and includes where materials within different ducts are in thermal or fluid communication through a common wall or membrane. For example, two ducts would be in contact where they contain fluids on opposite sides of a micro-porous membrane or where they contain fluids on opposite sides of a thermally-conductive, impermeable wall (e.g., a metal wall).

[0057] As used herein, "fluid communication" includes connected as part of the fluid flow of the system. When used generally, fluid communication relates to either a direct fluid connection where two points are directly connected by ducts, pipes, or tubes, and indirect fluid communication where two points are separated by one, or more unit operation, including, but not limited to, a heat exchanger, a fuel cell, a dehumidifier, a radiator, a holding tank, etc. As used herein, "in fluid communication" refers to in fluid communication in the direction of flow of fluid through the system. Thus, unless there is a loop the outlet of a tube cannot be in fluid communication with the inlet of the same tube.

[0058] As shown in FIGS. **1-45**, a heat and mass exchanger (HMX) system **10** is disclosed. For example, as shown in FIGS. **1***a,* **1***b,* **2**, **6-9**, **18-25**, **27-28**, **31**, and **40**, the HMX system **10** can include a plurality of exchange components **12**

extending across a HMX duct **14**, wherein a flow through the HMX duct **14** is cross-flow relative to the exchange components **12**. The exchange components **12** include a plurality of first elongated, hollow conduits **16** and a plurality of second elongated, hollow conduits **18**. Either the first elongated, hollow conduits **16** or the second elongated, hollow conduits **18** have water vapor permeable exterior walls **20** in order to facilitate mass transfer. The HMX system **10** is adapted for a carrier air stream **22** and a liquid desiccant stream **24** to flow in contact with opposite sides of the water vapor permeable exterior walls **20**.

[0059] In some embodiments, the water vapor permeable wall **20** comprises a material selected from the group consisting of a microporous plastic, structural porous duct covered with a microporous plastic, a structural porous duct covered with a water permeable polymer electrolyte membrane, or a combination thereof.

[0060] As used herein, the phrases water vapor permeable and micro-porous are used interchangeably. Where a tube wall, membrane, or material is water vapor permeable or micro-porous, the structure can be made of a material that is hydrophobic, and impermeable to liquids but permeable to water vapor. Such water vapor permeable materials are also referred to as mass transfer tubes or materials. Examples of solid or monolithic, water vapor permeable materials include sulfonated tetrafluoroethylene based fluoropolymer-copolymer (e.g., Nafion™, sold by DuPont), water conducting fluoropolymers, and non-fluorinated proton conducting polymers (e.g., NanoClear™, sold by Dais Analytic), and high density polyethelene (HDPE).

[0061] In some embodiments, the water vapor permeable materials are formed from fibers of hydrophobic materials. Examples include spunbond meltblown polymer materials. Such water vapor permeable materials are generally formed from hydrophobic materials. As used herein "hydrophobic" refers to materials with a contact angle of greater than 90° (e.g., at least 100°, at least 115°, at least 120°, or al least 135°).

[0062] In some embodiments, the HMX system **10** is adapted to transport a liquid desiccant stream **24** though and against an outer wall of a body selected from the HMX duct **14**, the first elongated, hollow conduits **16**, and the second elongated, hollow conduits **18**, while also transporting a carrier air stream **22** through and against an outer wall of a different body selected from the HMX duct **14**, the first elongated, hollow conduits **16**, and the second elongated, hollow conduits **18**. In some embodiments, the streams **22**, **24** are independently transported against an inside of an outer wall of the HMX duct **14**, the first elongated, hollow conduits **16**, and the second elongated, hollow conduits **18**

[0063] As shown in FIGS. **1***a*, **2**, **6-9**, and others, in some embodiments, the first elongated, hollow conduits **16** are each spaced apart from one another, and the second elongated, hollow conduits **18** are each spaced apart from one another.

[0064] In some embodiments, as shown in FIGS. **2**, **7**, **8**, **9**, **19**, **20**, and others, the exchange components **12** comprise tube-in-tube exchange components **26**, where each tube-in-tube component **26** comprises one first elongated, hollow conduit **16** within one second elongated, hollow conduit **18**. This configuration produces an inner flow channel **28** within the first elongated, hollow conduit **16** and an outer flow **30** channel external to the first elongated, hollow conduit **16** and adjacent a wall of the second elongated, hollow conduit **18**. Where some conduits **16**, **18**, **32** in a figure are designated as having water vapor permeable walls **20** (i.e., they are mass transfer conduits), those conduits not designated as being water vapor permeable can be heat transfer conduits.

[0065] As shown in FIGS. **26**, **33**, and **37**, the interior or exterior of the heat transfer conduits can have a hydrophilic surface **68**, e.g., they can be hydrophilic or include a hydrophilic coating or treatment. Such embodiments are particularly useful where the coolant **36** being used is an air stream or other gaseous stream. In such embodiments, the coolant stream **36** can also include a mist (e.g., water droplets), which can be provided via a mister, such as that shown in FIG. **15**. The combination of flowing air and the mist can provide psychrometric cooling. The hydrophilic coating can enhance the psychrometric cooling by facilitating a more even distribution of water on the hydrophilic surface **68**. As will be understood, in some embodiments, the misters can be positioned within the HMX duct **14** or within relevant flow chamber **28**, **30**, **34** necessary to introduce water to the hydrophilic surface **68**. Similarly, in some embodiments, the mister can be positioned upstream of the appropriate flow chamber **28**, **30**, **34** so that the mist is entrained in an air or gas stream and deposited on the hydrophilic surface **68**. For example, the mister could be disposed in an inlet distribution chamber **51**, **53**, **55**, **57**, **61***a*, **61***b* in fluid connection with the appropriate flow chamber **28**, **30**, **34**.

[0066] In some embodiments, the pluralities of first and second elongated, hollow conduits **16**, **18** extend laterally across the HMX duct **14**, and the HMX system **10** also includes a plurality of third elongated, hollow conduits **32** extending across the HMX duct **14**. In some embodiments, such as when the structures shown in FIGS. **27** & **29** are included sequentially in a single HMX system **10**, the third elongated, hollow conduits **32** extend laterally across the HMX duct. In some embodiments, as shown in FIG. **31**, the third elongated, hollow conduits **32** extend transverse to the first and second elongated, hollow conduits.

[0067] As will be apparent, the combinations of conduits **16**, **18**, **32** and the fluids that flow within and external to each can be varied. Examples include those shown in the figures, including FIGS. **26**, **32**, **33**, **36**, **37**, and **43**. It should be understood that, although FIGS. **26**, **32**, **33**, **36**, and **37** only show one exchanger component **12** for each type of component **12** (e.g., tube-in-tube, single tube, tube-in-tube-in-tube, and combinations) each stage of the HMX system **10** will include a plurality of such components (e.g., FIGS. **1***a*, **2**, etc.).

[0068] In some embodiments, as shown in FIGS. **33**, **34**, and **36**, each of the tube-in-tube exchanger components **26** includes one of the plurality of third elongated, hollow conduits **32**, within the first elongated, hollow conduit **16**. In such embodiments, the third elongated, hollow conduit **32** can define a central lumen **34** within the third elongated, hollow conduit **32**, and the inner flow channel **28** can be defined by an exterior of the third elongated, hollow conduit **32** and an interior of the first elongated, hollow conduit **16**. End caps **38**, **40** for supporting such tube-in-tube-in-tube components are shown in FIGS. **34** & **35**.

[0069] In some embodiments, as shown in FIGS. **21** & **26**, the HMX system **10** is adapted so that a coolant stream **36** flows through the inner channel **28**, a liquid desiccant stream **24** flows through the outer channel **30**, and a carrier air stream **22** flows through the HMX duct **14**. In FIGS. **21**, **22**, & **23**, the "+" symbol indicates fluid flow out of the drawing toward the observer, while a "•" represents fluid flow into the drawing away from the observer. Thus, in some embodiments, as shown in FIG. **21**, the HMX system **10** is configured so that the coolant stream **36** and the liquid desiccant stream **24** flow in a counter-flow arrangement.

[0070] As used herein, "coolant stream" relates to a fluid stream containing a heat transfer fluid, such as those generally used to cool an engine, ambient air or air recirculated from an air conditioned space, water, or a combination of air and water for psychrometric cooling. In some instances, such as when the liquid desiccant is being regenerated, the coolant stream **36** will be introduced into the HMX system **10** from an engine in the heated state and the coolant stream **36** will be used to heat the liquid desiccant stream. In other embodiments, the coolant stream will be used to cool the liquid desiccant stream in order to facilitate dehumidification of carrier air that will be transported to an air conditioned space.

[0071] In some embodiments, as shown in FIG. **22**, the HMX system **10** is adapted so that a carrier air stream **22** flows through the inner channel **28**, a liquid desiccant stream **24** flows through the outer channel **30**, and a coolant stream **36** flaws through the HMX duct **14**. In some such embodiments, the HMX system **10** is configured to flow the carrier air stream **22** and the liquid desiccant stream **24** in a counter-flow arrangement.

[0072] In some embodiments, as shown in FIG. **23**, the HMX system **10** is adapted so that a liquid desiccant stream **24** flows through the inner channel **28**, a carrier air stream **22** flows through the outer channel **30**, and the coolant stream **36** flows through the HMX duct **14**. In some embodiments, the HMX system **10** is configured to flow the liquid desiccant stream **24** and the carrier air stream **22** in a counter-flow arrangement.

[0073] In some embodiments, each of the first elongated, hollow conduits **16** is longer than each of the second elongated, hollow conduits **18**. As shown in FIG. **28**, in such embodiments, a first end of each of the first elongated, hollow conduits **16** can sealably engage a receiving portion of the first outer manifold plate **54**, while a second end of the first elongated, hollow conduit **16** sealably engages a receiving portion of the second outer manifold plate **56**. Similarly, a first end of each of the second elongated, hollow conduits **18** can sealably engage a receiving portion of the first inner manifold plate **50** while a second end attic second elongated, hollow conduit **18** sealably engages a receiving portion attic second inner manifold plate **52**.

[0074] In some embodiments, as shown in exploded view FIG. **39**, each tube-in-tube exchanger component **26** comprises a first end cap **38** and a second end cap **40**. The first end cap **38** can sealably engage first ends of a set of first and second elongated, hollow conduits **16**, **18**, while the second end cap **40** can sealably engage second ends of the set of first and second elongated, hollow conduits **16**, **18**. The first end cap **38** can include at least one first end cap inner opening **42** extending to the inner flow channel **28** and at least one first end cap outer opening **44** extending to the outer flow channel **30**. The second end cap **40** can include at least one second end cap inner opening **46** extending to the inner flow channel **28** and at least one second end cap outer opening **48** extending to the outer flow channel **30**.

[0075] Depending on the design of the first and second end caps **38**, **40**, the length of the first and second elongated, hollow conduits **16**, **18** can be varied while still achieving a quality seal with the manifolds **50**, **52**, **54**, **56**. Thus, in some embodiments, the first and second elongated, hollow conduits **16**, **18** can be the same length, while the first and second elongated, hollow conduits **16**, **18** can be different lengths in other embodiments. In some embodiments, the first elongated, hollow conduits **16** can be longer than the second elongated, hollow conduits **18**, while the first elongated, hollow conduits **16** can be shorter than the second elongated, hollow conduits **18** in other embodiments.

[0076] In some embodiments, as shown in FIGS. **28** & **40**, the HMX system **10** includes first and second inner manifold plates **50**, **52** on opposite sides of the HMX duct **14**; and first and second outer manifold plates **54**, **56** on opposite sides of the HMX duct **14**, wherein the first and second inner manifold plates **50**, **52** are between the first and second outer manifold plates **54**, **56**. In such embodiments, as shown in FIG. **40**, the first inner manifold plate **50** and the first outer manifold plate **54** sealably engage the first end cap **38** of each tube-in-tube exchanger component **26**, and the second inner manifold plate **52** and the second outer manifold plate **56** sealably engage the second first end cap **40** of each tube-in-tube exchanger component **26**.

[0077] In some embodiments, as shown in FIGS. **28**, **34**, and **40**, the inner manifold plates **50**, **52** are adapted for feeding a first fluid into an outer flow channel **30** of a tube-in-tube component **26**, while the outer manifold plates **54**, **56** are adapted for feeding a second fluid into an inner flow channel **28** a tube-in-tube component **26**. Where applicable, as shown in FIG. **34**, third conduit manifolds **59***a*, **59***b* are adapted for feeding a third fluid into a central lumen **34** of a tube-in-tube-in-tube component.

[0078] As best shown in FIG. **20**, the inner manifold plates **50**, **52** can form one wall of first and second inner distribution chambers **51**, **53**, while the outer manifold plates **54**, **56** can form one wall of first and second outer distribution chambers **55**, **57**. Thus, fluid flowing into the first inner distribution chamber **51** is distributed into the inner flow channel **28** of the various tube-in-tube exchange components **26** then exits into the second inner distribution chamber **53** before exiting the HMX system **10**. Similarly, a fluid flowing into the first outer distribution chamber **55** is distributed into the outer flow channel **30** of the various tube-in-tube exchange components **26** then exits into the second inner distribution chamber **57** before exiting the HMX system **10**. Of course, either or both of these flow regimes can be reversed depending on the desired flow pattern.

[0079] As shown in FIG. **34**, where a tube-in-tube-in-tube configuration is used, the HMX system **10** can also include first and second 3rd conduit manifolds **59***a*, **59***b*. In such embodiments, the first and second 3rd conduit manifolds can form one wall of first and second lumen distribution chambers **61***a*, **61***b*. In such embodiments, fluid flowing into the first lumen distribution chamber **61***a* is distributed into the inner central lumen **34** of the various tube-in-tube-in-tube exchange components then exits into the second lumen distribution chamber **61***b* before exiting the HMX system **10**.

[0080] In some embodiments, as shown in FIGS. **2** & **7**, and **28**, the HMX system **10** includes first and second inner manifold plates **50**, **52** on opposite sides of the HMX duct **14**; and first and second outer manifold plates **54**, **56** on opposite sides of the HMX duct **14**. In such embodiments, the first and second inner manifold plates **50**, **52** are between the first and second outer manifold plates **54**, **56**, and the first and second inner manifold plates **50**, **52** engage first and second ends of each of the second elongated, hollow conduits **18**, and the first and second outer manifold plates **54**, **56** engage first and second ends of each of the first elongated, hollow conduits **16**.

[0081] In some embodiments, the HMX system **10** includes a plurality of flow disrupters **58** extending from at least one wall **60** of the HMX duct **14**. In some embodiments, the flow disrupters **58** extend across the HMX duct **14**. In some embodiments, at least one flow disrupter **58** can extend laterally across the HMX duct **14**. In some embodiments, at least one flow disrupter **58** can extend transversely across the HMX duct **14**.

[0082] In some embodiments, an exterior **62**, of at least one of the tube-in-tube exchange components **26** can include a flow disrupter **58**. For example, FIGS. **41**, **42** & **43** show tube-in-tube components **26** where the exterior has the shape of an air foil. In some embodiments, the flow disrupters **58** have a shape selected from the group consisting of airfoils, projections, walls, and fins.

[0083] In some embodiments, as shown in FIG. **25**, the HMX duct **14** comprises first and second longitudinal walls **64**, **66** opposite one another, and the flow disrupters **58** comprise at least one first fin **58***a* extending from the first longitudinal wall **64** partially across the HMX duct **14** and at least one second fin **58***b* extending from the second longitudinal wall **66** partially across the HMX duct **14**. In some embodiments, as shown in FIG. **25**, each of the fins **58***a*, **58***b* extend between different sets of tube-in-tube exchange components **26**. As shown in FIG. **25**, in some embodiments, the flow disruptors **58** cause flow through the HMX duct **14** to travel in an s-shaped path or another path that extends the length of the path of fluid passing through the HMX system **10** (e.g., through the HMX duct, the inner flow channel, the outer flow channel, the inner lumen, or some other flow channel). Similarly, in some embodiments, the flow disruptors increase the turbulence of fluid passing through the HMX system **10**.

[0084] In some embodiments, as shown in FIG. **24**, the flow disruptors **58** extend a portion across the HMX duct **14** in one direction (e.g., transversely) and completely across the HMX duct **14** in a second direction (e.g., laterally). As shown in FIG. **24**, the flow disruptors can be bars or rods, which can have uniform or variable cross-sections.

[0085] In some embodiments, the flow disruptors **58** can extend from an exterior of the first conduit **16** tube-in-tube component **26**. In such embodiments, as shown in FIG. **44**, the flow disruptor **58** can extend partially or completely across the distance from the first conduit **16** to the second conduit **18**, so that fluid flowing through the outer flow channel **30** takes a longer or more tortuous path through the outer flow channel **30** than the fluid would take in the absence of the flow disruptor **58**. For example, as shown in FIG. **44**, fluid flowing through the outer flow channel **30** can be forced to take a spiral path.

[0086] In some embodiments, the flow disruptors **58** extend less than 80% across, or less than 70% across, or less than 60% across, or less than 50% across, or less than 40% across the longitudinal direction. In some such embodiments, the fins **58***a*, **58***b* extend at least 10% across, or at least 20% across, or at least 30% across, or at least 40% across, or at least 50% across the longitudinal direction.

[0087] As is apparent from the discussions herein, the HMX devices **10** described herein can he useful in desiccant regeneration systems. Additional details of liquid desiccant regeneration systems can be found in U.S. patent application Ser. No. ______, entitled "Liquid Desiccant Regeneration System, Systems Including the Same, and Methods of Operating the Same," by Daniel A. Betts and John Kaufman, filed Feb. 17, 2015, the entirety of which is incorporated herein by reference.

[0088] The following provides a variety of embodiments of heat and mass transfer devices and systems as described herein. Although discussed in different groups, it should be understood that the consistent with the spirit of the disclosure, various unit operations from one embodiment can be exchanged with, added to, or taken from another embodiment.

First Discussion

[0089] FIG. **1***a* shows an embodiment of a heat and mass transfer device (**2100**) with distinct and separate heat transfer tubes (**2001**) and mass transfer tubes (**2002**), while FIG. **1***b* is a cross-sectional view of FIG. **1***a* The mass transfer tubes (**2002**) are retained by and sealed against two mass transfer manifold plates (**2012**). Longer heat transfer tubes (**2001**) are retained by and sealed against two heat transfer manifold plates (**2011**) and two mass transfer manifold plates (**2012**). As shown in FIGS. **1-15**, in some embodiments, the coolant (**2003**) is introduced into heat transfer tubes (**2001**) parallel to and interspersed among mass transfer tubes (**2002**) carrying liquid desiccant (**2004**), which is introduced between the heat transfer manifold plate (**2011**) and the mass transfer manifold plate (**2012**). The air to be dehumidified (**2005**) passes perpendicular to the axes of the mass transfer tubes (**2002**) and the heat transfer tubes (**2001**). Dehumidified air (**2006**) exits the device after it passes by the plurality of heat transfer tubes (**2001**) and mass transfer tubes (**2002**). As water vapor in the air to be dehumidified (**2005**) is absorbed by the liquid desiccant (**2004**) in the mass transfer tubes (**2002**), heat is transferred to the air being dehumidified (**2005**). This heat is then transferred from the air being dehumidified (**2005**) to the coolant (**2003**) in the heat transfer tubes (**2001**). In this fashion, the air being dehumidified (**2005**) acts as a heat transfer medium between the liquid desiccant (**2004**) and the coolant (**2003**), and the air being dehumidified (**2005**) is maintained at a constant or close to constant temperature.

[0090] FIG. **2** shows a second embodiment of a heat and mass transfer device (**2100**) that has distinct and concentric heat transfer tubes (**2001**) and mass transfer tubes (**2002**). In this embodiment, the heat transfer tubes (**2001**) are concentric and internal to larger diameter mass transfer tubes (**2002**). The mass transfer tubes (**2002**) are retained by and sealed against two mass transfer manifold plates (**2012**). Longer heat transfer tubes (**2001**) are retained by and sealed against two heat transfer manifold plates (**2011**). This arrangement leaves a gap between the outer diameter of the mass transfer tubes (**2002**) and the inner diameter of the heat transfer tubes (**2001**) into which the liquid desiccant may flow when introduced between the heat transfer manifold plate (**2011**) and the mass transfer manifold plate (**2012**). The air to be dehumidified (**2005**) passes perpendicular to the axis of the mass transfer tubes (**2002**). Dehumidified air (**2006**) exits the device after it passes by the plurality of mass transfer tubes (**2002**). As water vapor in the air (**2005**) is absorbed by the liquid desiccant (**2004**), the temperature of the liquid desiccant (**2004**) in the mass transfer tubes (**2002**) tends to increase. A coolant (**2003**) is introduced into the smaller, interior heat transfer tubes (**2001**), which reduces the magnitude of temperature increase of the liquid desiccant (**2004**), with which it is in thermal contact. The heat transfer tubes (**2001**) may be made entirely of a compatible material, not subject to corrosion by the liquid desiccant (**2004**), or they may be constructed from Aluminum or another material with high thermal conductivity, and then coated with a suitable barrier including PP, PPS, PVC, PTFE, and PVDF, among others, in either case, thin-walled tubing is desirable for improved heat transfer from the liquid desiccant (**2004**) to the coolant (**2003**). Other methods to increase heat transfer may also be used, such as fins, wall corrugations and features that increase fluid turbulence and heat transfer area.

[0091] As shown in FIGS. **10-13**, some embodiments of the dehumidifying heat exchanger system include a liquid desiccant pump (**2015**) placed downstream from the dehumidifying heat exchanger. This placement ensures a lower liquid desiccant pressure as compared to the air to be dehumidified. Use of this approach reduces the likelihood of liquid desiccant leaks, even in the event of abrasive damage, pinholes or other imperfections of the microporous or solid electrolyte membrane of the mass transfer tubes.

[0092] The mass transfer tubes in this section, and throughout the specification, may be produced using various materials and methods that achieve the desired water vapor transport from the humid air to the liquid desiccant and provide chemical compatibility with the liquid desiccant, FIG. **3** shows a cross-sectional view that describes an embodiment of the mass transfer tube (**2002**). In order to contain the liquid desiccant in the mass transfer tube (**2002**), a hydrophobic and microporous membrane (**2021**) with porosity including, but not limited to a range of 0.05 microns to 0.5 microns, may be used. The combination of small pores and a hydrophobic material prevents water from wicking through the microporous membrane under normal operating conditions (e.g., pressures tinder 20 psi). However, when the pressure inside the tube is increased above a breakthrough pressure liquid water can seep through the pore structure.

[0093] As used herein, “breakthrough pressure” relates to the minimum pressure at which liquid water will cross a hydrophobic microporous membrane that is only water-vapor permeable at lower pressures. For example, the breakthrough pressure of a hydrophobic sintered material with a porosity of 0.1 microns may be approximately 60 psi.

[0094] When operated at a breakthrough pressure, water will pass through to the surface of the hydrophobic, microporous material to produce a thin sheet of water around the surface. An alternate technique for producing a thin sheet of water on the surface of the ducts is utilizing a hydrophilic, microporous material under lower pressures. Mister sprayheads can be used to introduce water droplets for evaporative cooling anywhere herein where a hydrophobic, microporous material at a breakthrough pressure or a hydrophilic, microporous material is used. FIG. **15** shows an example of a mister configuration.

[0095] To promote water vapor transport, in some embodiments, a thickness of the microporous membrane (**2021**) includes, but is not limited to the range of 10 microns to 50 microns and its open area should exceed 50%. In some embodiments, the open area is greater than 70%. For the purpose of mechanically supporting this thin, microporous membrane, and to prohibit the collapse of the membrane tube in the case that the liquid desiccant is at a lower pressure than the surrounding ambient air, a structural, internal support tube (**2020**) can be provided. This design approach, with the microporous membrane (**2021**) covering the outside surface of the structural support tube (**2020**), permits the liquid desiccant to be nearest to the passing air to be dehumidified, and promotes water vapor transport across the membrane (**2021**). Both the structural tube (**2020**) and membrane (**2021**) may be produced from a suitable material such as PVDF, PP, PES, PPS, PVC, PTFE, and other suitable materials. Examples of mass transfer tubes include micro- and ultra-filtration tubes include those produced by Berghof from PES and PVDF membranes applied to single and dual layer supports.

[0096] Another example includes FIG. **4**, which shows a product from Porex, which is an assembly of multiple filtration tubes housed in a larger cylindrical vessel and is used for solids removal from water at elevated pressures. These commercial filtration tubes are produced from PVDF, PE and PES and employ microporous membranes with porosity in the range of 0.05 microns to 0.5 microns, which are applied to porous substrates with porosity in the range of 10 microns to 100 microns. Wall thickness of the tubular substrate can be ranges that include, but are not limited to 0.005" to 0.050". The placement of the microporous membrane can be on the outside surface of the tubular substrate.

[0097] In a second embodiment of the mass transfer tube (**2002**), a structural, porous tube (**2020**) is again used as a substrate, onto which a solid electrolyte membrane (**2021**) is applied. The porous substrate (**2020**) can include a sintered material such as PTFE, PVDF, PP or other suitable material, with porosity including, but not limited to the range of 10 microns to 500 microns. The electrolyte membrane (**2021**), which selectively transports water and not gases, is applied onto the outer surface of the substrate tube (**2020**) through spraying, dipping or other deposition methods. In some embodiments, the thickness range of the electrolyte membrane (**2021**) is in a range that includes, but is not limited to 10 microns to 100 microns. A wall thickness range of the structural porous substrate tube (**2020**) includes, but is not limited to 0.005" to 0.050". In some embodiments, the porous substrate tube (**2020**) is formed of hydrophilic materials, in order to promote transfer of water through the sintered material and to the surface of the microporous membrane.

[0098] In a third embodiment of the mass transfer tube (**2002**), a structural porous or perforated tube (**2020**) is used as a mechanical support, onto which a microporous membrane (**2021**) or an aforementioned solid electrolyte membrane (**2021**) is attached. A porous tube (**2020**) may be produced from sintered PVDF, PP or other suitable material with porosity in the range that includes, but is not limited to 10 microns to 500 microns. A perforated tube (**2020**,**4020**) with porosity in the range that includes, but is not limited to 0.05" to 0.5" may be produced by injection or compression molding PP, PVDF, or other suitable material. The structural tube (**2020**/**4020**) may have circular cross section, or it may use a foil-shape or other combination of circular and angular sections that result in improved air flow directed perpendicular to its axis (FIG. **5**). Certain cross sections, such as the foil-shape will enable assembly of the porous and perforated structures (**2020**) and membranes (**2021**) from sheet materials, bonded at the trailing edge using heat staking, chemical adhesives and other methods known to one versed in the art.

[0099] One application for the dehumidifying heat exchanger is the aforementioned removal of latent heat from an air stream. A second application for the invention is the removal of sensible heat from an air stream—the second stage in producing dry, cool air for building air conditioning and refrigeration. FIGS. **6**, **7**, **8**, and **9** describe this two-stage air conditioning process to produce dry, cool air using two consecutive heat and mass transfer devices (**2100**), respectively. As it relates to FIGS. **6-9**, cooling of a dehumidified air stream

(**2006**) may be accomplished without increasing its humidity through heat exchange with a secondary air stream (**2009**) whose temperature is reduced by evaporative cooling with water (**2008**). The heat and mass transfer device (**2100**) of design shown in FIGS. **1***a,* **1***b,* or FIG. **2** may be used for this purpose by substituting water (**2008**) for the liquid desiccant (**2004**). In this second application, the dehumidified process air stream (**2006**) is introduced into heat transfer tubes (**2001**) that exchange heat only (not water). Ambient air, e.g., return air (**2009**) from the building, is directed across the mass transfer tubes (**2002**) where it picks up water vapor and experiences a reduction in temperature due to evaporative cooling. This cooled air (**2009**) then exchanges heat directly with the air in the heat transfer tubes (**2001**) when using the design of FIGS. **1***a* & **1***b,* or with the subsequent mass transfer tubes (**2002**), when using the design of FIG. **2**, which in turn exchange heat with the internal, concentric heat transfer tubes (**2001**). Dry, cool air (**2007**) is produced as a result of consecutively passing humid, hot air (**2005**) through two of the heat and mass transfer devices (**2100**); one configured for dehumidification of humid air (**2005**), and the second configured for humidification and cooling of a secondary air stream (**2009**).

[0100] In one variation, chilled water or refrigerant from a vapor compression cycle is introduced into the heat transfer tubes (**2001**) of the dehumidifying heat and mass transfer device. The chilled water or refrigerant serves as the coolant (**2003**), which exchanges heat with the liquid desiccant (**2004**) as in earlier embodiments. Depending on coolant (**2003**) temperature and flow rate, the liquid desiccant (**2004**) may be maintained at or reduced from its inlet temperature, further promoting dehumidification of the process air (**2005**) and potentially achieving the desired building process air temperature without the use of a second indirect cooling device.

[0101] FIG. **10** shows the implementation of the heat and mass transfer devices (**2100**) in an air conditioning system (**2200**) that is fueled with natural gas, provides dry, cool air, and produces electricity as a by-product. Heat from a fuel cell is used to regenerate the liquid desiccant (**2004**) by liberating the water absorbed in the dehumidifying heat and mass transfer device (**2100**). This dry air (**2006**) is subsequently introduced into the heat transfer tubes (**2001**) of a second heat and mass transfer device (**2100**), where it is indirectly cooled by a secondary air stream (**2009**) that is undergoing evaporative cooling.

[0102] in some embodiments, a heat and mass transfer device **2100** is described. The heat and mass transfer device can include a heat transfer duct system **2102**, a mass transfer duct system **2104**, and an air transport duct **2106**. As best shown in FIGS. **1***a,* **1***b,* **2**, & **6-9**, portions of the heat transfer duct system **2102** and the mass transfer duct system **2104** extend through the air transport duct **2106**. As should be apparent the operations shown in FIGS. **6-9** can be separate unit operations or combined into a single HMX system. The mass transfer duct system **2104** comprises a water vapor permeable wall **2108**. As used herein, "water vapor permeable" refers to a material that is permeable to water vapor, but does not allow the transport of water from one side of the material (wall, membrane, etc.) to the other under standard pressures. For example, "water vapor permeable" membranes include microporous, hydrophobic materials.

[0103] In some embodiments, the heat transfer duct system **2102** includes a plurality of heat transfer ducts **2110** in fluid communication with a heat transfer fluid header chamber **2112** on one end and a heat transfer fluid exhaust chamber **2114** at an opposite end of the heat transfer ducts **2110**. In some embodiments, the heat transfer ducts **2110** can be heat transfer tubes **2001** having a cylindrical cross-section. In some embodiments, the individual heat transfer ducts **2110** can be parallel to one another. In some embodiments, the flow through the air transport duct **2106** can be perpendicular to the flow through the heat transfer ducts **2110**. Although referred to as "heat transfer fluid," it should be understood that in a closed cycle the heat transfer fluid will be relatively cold in some portions of the system (such as prior to cooling ambient air in an air conditioner), and warm in other portions of the system (after cooling the ambient air in an air conditioner). As used herein, "warm" is used to refer to temperatures at or above room temperature, for example, at least 25° C., or at least 30° C., while "cool" is used to refer to temperatures below room temperature, for example, below 20° C., or below 15° C.

[0104] In some embodiments, the mass transfer duct system **2104** includes a plurality of mass transfer ducts **2116** in fluid communication with a desiccant header chamber **2118** on one end and a desiccant exhaust chamber **2120** at an opposite end of the mass transfer ducts **2116**. In some embodiments, the mass transfer ducts **2116** can be mass transfer tubes **2002** having a round cross-section. In some embodiments, the individual mass transfer ducts **2116** can be parallel to one another. In some embodiments, the flow through the air transport duct **2106** can be perpendicular to the flow through the mass transfer ducts **2116**.

[0105] In some embodiments, such as those shown in FIGS. **1***a* & **1***b,* the plurality of mass transfer ducts **2116** are spaced apart from and interspersed with the plurality of heat transfer ducts **2110**. As used herein, "interspersed with" is used to refer to arrangements where the ducts are independently placed and separated, but located in the same region, as shown in FIGS. **1***a* and **1***b*. The phrase "interspersed with" is intended to distinguish from arrangements where one duct is within another duct, as shown in FIG. **2**.

[0106] As shown in FIG. **2**, in some embodiments, each heat transfer duct **2110** is positioned within a mass transfer duct **2116**. The mass transfer ducts **2116** are can be spaced apart from one another in some embodiments. In some embodiments, one heat transfer duct **2110** is positioned coaxially within each mass transfer duct **2116**.

[0107] In some embodiments, the walls of the heat transfer ducts **2110** comprise a material selected from the group consisting of polyvinylidene difluoride (PVDF), polypropylene (PP), polyvinyl chloride (PVC), polyphenylene sulfide (PPS), polyethersulfone (PES), polytetrafluoroethylene (PTFE), and combinations thereof.

[0108] In some embodiments, the walls of the heat transfer ducts **2110** do not contain metal. This can be advantageous in embodiments where the heat transfer duct **2110** is within the mass transfer duct **2116**, because such embodiments can expose the exterior of the heat transfer duct **2110** to a liquid desiccant flowing within the mass transfer duct **2116**. In some embodiments, the wall of the heat transfer duct can be formed of a metal coated with a non-corrosive coating, e.g., polyvinylidene difluoride (PVDF), polypropylene (PP), polyvinyl chloride (PVC), polyphenylene sulfide (PPS), polyethersulfone (PES), polytetrafluoroethylene (PTFE), and combinations thereof.

[0109] As shown in FIGS. **1-15**, in some embodiments, each heat transfer duct **2110** is longer than each mass transfer duct **2116**. In some embodiments, the heat transfer ducts **2110** are the same length. In some embodiments, the mass transfer ducts **2116** are the same length.

[0110] As best shown in FIG. **1***b*, in some embodiments, a first end of each heat transfer duct **2110** is mounted to an opening **2122** in a heat transfer header plate **2124**, and an opposite end of each heat transfer duct **2110** is mounted to an opening **2126** in a heat transfer exhaust plate **2128**. In some embodiments, a first end of each mass transfer duct **2116** is mounted to an opening **2130** in a mass transfer header plate **2132**, and an opposite end of each mass transfer duct **2116** is mounted to an opening **2134** in a mass transfer exhaust plate **2136**.

[0111] As shown in FIG. **1***b*, in embodiments where the flow within the mass transfer ducts **2116** is counter to the flow within the heat transfer ducts **2110**, at least a portion of the desiccant header chamber **2118** can be between the heat transfer exhaust plate **2128** and the mass transfer header plate **2132**. In such embodiments, at least a portion of the desiccant exhaust chamber **2120** is between the heat transfer header plate **2124** and the mass transfer exhaust plate **2136**.

[0112] Although not shown, it will be easily understood that, in embodiments where the flow within the mass transfer ducts **2116** is in the same direction as the flow within the heat transfer ducts **2110**, at least a portion of the desiccant header chamber **2118** is between the heat transfer header plate **2124** and the mass transfer header plate **2132**. In such embodiments, at least a portion of the desiccant exhaust chamber **2120** is between the heat transfer exhaust plate **2128** and the mass transfer exhaust plate **2136**.

[0113] In some embodiments, no mass exchange occurs between the heat transfer duct system **2102** and the mass transfer duct system **2104**. In some embodiments, the ducts **2110**, **2116** can be attached to the respective header plate **2124**, **2132** and/or exhaust plate **2128**, **2136** in a manner that prevents leaks from one side of the plate **2124**, **2128**, **2132**, **2136** to the other. Examples of techniques that can be used to produce such seals include, but are not limited to, (a) compression forces transferred through an elastomer o-ring, (h) welding, (c) screwed on fastening, (d) chemical bonding, and (e) combinations thereof. As is evident from FIGS. **1***a* & **1***b*, in some embodiments, the heat transfer ducts **2110** must interact with openings in the mass transfer plates **2132**, **2136** to form a liquid tight seal in order to prevent fouling of the heat transfer fluid stream and the liquid desiccant stream.

[0114] In some embodiments, each mass transfer duct **2116** is longer than each heat transfer duct **2110**. Such embodiments are identical to those shown in FIGS. **1***a*, **1***b*, and **2**, with the exception that heat transfer fluid is fed to the mass transfer ducts **2116** and the liquid desiccant is fed to the heat transfer duct **2110**.

[0115] In some embodiments, the mass transfer duct system **2104** comprises walls **2019** formed from a water vapor permeable material. In some embodiments, the wall(s) **2019** can include a porous support material **2020/4020** (e.g., a scaffolding, such as that shown in FIGS. **3** & **5**) and a water vapor permeable material **2021**. Examples of wall **2019** materials are those selected from the group consisting of a microporous plastic, structural porous duct **2020/4020** covered with a microporous plastic **2021**, a structural porous duct **2020/4020** covered with a water-permeable, microporous polymer electrolyte membrane **2021**, or a combination thereof. As used herein, "covered" includes, but is not limited to, instances where a material is coated onto a substrate and instances where a material (such as a film) is wrapped over or shrink wrapped onto the substrate. An example of a porous support material **2020** is shown in FIG. **5**.

[0116] In some embodiments, the contents of the heat transfer duct system **2102** are in thermal communication with contents of the air transport duct **2106** via a wall **2103**. The wall **2103** can include a material selected from the group consisting of polyvinylidene difluoride (PVDF), polypropylene (PP), polytetrafluoroethylene (PTFE), polyvinyl chloride (PVC), polyphenylene sulfide (PPS), polyethersulfone (PES), metal, and combinations thereof in some embodiments, the wall can be formed of a metal coated by polyvinylidene difluoride (PVDF), polypropylene (PP), polytetrafluoroethylene (PTFE), or combinations thereof. In other embodiments, the wall can be formed of polyvinylidene difluoride (PVDF), polypropylene (PP), polytetrafluoroethylene (PTFE), polyvinyl chloride (PVC), polyphenylene sulfide (PPS), polyethersulfone (PES), or combinations thereof. Examples of metal that can be useful include, but are not limited to, titanium, stainless steel, and other corrosion resistant metals or alloys.

[0117] In some embodiments, a heat transfer fluid stream **2003** is fed into an inlet **2102**$_{IN}$ of the heat transfer duct system **2102**. In some embodiments, the heat transfer fluid stream comprises a heat transfer fluid selected from a group that includes, but is not limited to, air, ethylene glycol, water, ammonia, fluorocarbons, chlorofluorocarbons, sulfur dioxide, halons, hydrocarbons, and mixtures thereof. As used herein, "halons" has its standard meaning and includes haloalkanes.

[0118] In some embodiments, a liquid desiccant stream **2004** is fed into an inlet **2104**$_{IN}$ of mass transfer duct system **2104**. In some embodiments, a desiccant (e.g., salt) concentration of the liquid desiccant stream **2004** is lower at an outlet **2104**$_{OUT}$ of the mass transfer duct system **2104** than at the inlet **2104**$_{IN}$ of the mass transfer duct system **2104**.

[0119] In some system embodiments, such as those shown in FIGS. **6-14**, an air conditioning system **2200** that includes a first heat and mass transfer device **2100**, and a second heat and mass transfer device **2100**$_B$ and any variants thereof described herein, is described. In some embodiments of the air conditioning system **2200**, an exhaust of the first air transport duct **2106**$_{A,\ OUT}$ is in fluid communication with an inlet to the second heat transfer duct system **2102**$_{B,\ IN}$. For clarity, the subscript A will be used to refer to features of the first heat and mass transfer device **2100**$_A$, while the subscript B will be used to refer to features of the second heat and mass transfer device **2100**$_B$, and the subscript C to refer to features of the third heat and mass transfer device **2100**$_C$.

[0120] In some embodiments, air **2009** flowing through the second air transport duct **2106**$_B$ is humidified by a liquid stream **2008** flowing in the second mass transfer duct **2102**$_B$.

[0121] In some air conditioning system embodiments:

[0122] a first heat transfer fluid stream is fed into the first heat transfer duct system **2102**$_A$, **2112**$_A$;

[0123] a high concentration liquid desiccant stream is fed into the first mass transfer duct system **2104**$_A$, **2118**$_A$;

[0124] air being conditioned is fed into the first air transport duct **2106**$_A$;

[0125] dehumidified air exiting the first air transport duct **2106**$_A$ is fed into the second heat transfer duct system **2102**$_B$, **2112**$_B$;

[0126] water is fed into the second mass transfer duct system **2104**$_B$, **2118**$_B$; and

[0127] secondary air **2009** is fed into the second air transport duct **2106**$_B$.

[0128] In such embodiments, the second mass transfer duct system **2104**$_B$ can include a wall (e.g., walls of the mass transfer ducts **2116**$_B$) comprising a mass transfer membrane that is selectively permeable to water vapor. In such embodiments, the secondary air **2009** is humidified by water passing through the mass transfer membrane of the mass transfer ducts **2116**$_B$ to produce humidified process air **2010**. In such embodiments, the mass transfer ducts **2116**$_B$ can be formed of a water-vapor permeable membrane and operated at a pressure above the breakthrough pressure of water-vapor permeable membrane, or the mass transfer ducts **2116**$_B$ can be formed of a water permeable, microporous material. In either case, a thin film of water can be produced on the exterior of the mass transfer ducts **2116**$_B$ in order to facilitate humidification of the secondary air **2009**.

[0129] In some embodiments, the first heat transfer fluid stream **2003** comprises air and the second heat transfer fluid stream comprises air **2009** that undergoes evaporative cooling with water **2008** that sheets over the surface of the mass transfer ducts **2116**$_B$. In some embodiments, the mass transfer ducts **2116**B can have water permeable, microporous walls. In other embodiments, the mass transfer ducts **2116**B can have walls formed from water vapor permeable walls and the water pressure can be at or above the breakthrough pressure. In some embodiments, an exhaust stream from the second heat transfer duct system **2102**$_B$, **2114**$_B$ comprises dehumidified, cooled air **2007** that is supplied to a space being air conditioned. Examples of such embodiments are shown in FIGS. **10-14**.

[0130] In some embodiments, a low concentration liquid desiccant stream exiting the first mass transfer duct system **2104**$_{A,OUT}$, **2120**$_A$ is regenerated to produce a high concentration liquid desiccant stream fed into an inlet of the first mass transfer duct system **2104**$_{A,IN}$, **2118**$_A$.

[0131] In some embodiments, the air conditioning system **2200** includes a fuel cell **2138**. In some embodiments, the heat (e.g., from the coolant used in the fuel cell) produced by the fuel cell **2138** is used to regenerate the liquid desiccant stream by driving water out of the liquid desiccant stream and produce a high concentration liquid desiccant stream. Examples of such embodiments are shown in FIGS. **10-14**.

[0132] In some embodiments, such as those shown in FIGS. **10-14**, the air conditioning system **2200** includes a regeneration system **2140**. In some embodiments, such as the one shown in FIG. **10**, the regeneration system relies upon a counter-flow heat exchanger **2145**. In some embodiments, warm heat transfer fluid (e.g., hot water) from the fuel cell **2138** is fed into the heat transfer line inlet **2152** of the heat exchanger **2145** and the heat transfer fluid exiting the heat transfer line outlet **2154** is returned to the fuel cell **2138**. A low concentration liquid desiccant stream from the desiccant exhaust chamber **2120**A can be fed into a heat exchanger desiccant inlet **2156** of the heat exchanger **2145**. The low-concentration liquid desiccant is heated as is passes through the heat exchanger **2145**. The low-concentration liquid desiccant exiting the heat exchanger desiccant outlet **2158** then proceeds to a mass transfer unit **2150**.

[0133] The low-concentration liquid desiccant from the heat exchanger desiccant outlet **2158** enters the mass transfer unit **2150** through the mass transfer desiccant inlet **2160** then flows through the mass transfer desiccant ducts **2161** before exiting the mass transfer desiccant outlet **2162**. The fuel cell exhaust **2163** is fed into the mass transfer heating inlet **2164**, passes through a mass transfer heating ducts **2165** and exits the mass transfer heating outlet **2166**. Water in the liquid desiccant stream which was previously heated in the heat exchanger **2145** is driven out of the mass transfer desiccant ducts **2161** in the form of water vapor. In some embodiments, the mass transfer desiccant ducts **2161** have water vapor permeable, microporous walls to drive water out of the low-concentration liquid desiccant and produce a high concentration liquid desiccant stream exiting the mass transfer desiccant outlet **2162**.

[0134] The high-concentration liquid desiccant stream exiting the mass transfer desiccant outlet **2162** can then be fed into a radiator **2168** for cooling. The high concentration liquid desiccant stream can then be fed into the desiccant header chamber **2118**$_A$ of the first heat and mass transfer device **2100**$_A$.

[0135] In other embodiments, such as those shown in FIGS. **11-14**, the regeneration system **2140** can include a moisture removal duct **2106**C, and a desiccant regeneration duct **2116**C that extends through the moisture removal duct **2106**C, wherein water vapor from the liquid desiccant stream in the desiccant regeneration duct **2116**C selectively passes through a desiccant regeneration duct membrane forming the wall of the duct **2116**C and into the moisture removal duct **2106**C where it is entrained in the humidified air **2011**. In some embodiments, such as those shown in FIGS. **11-13**, warm coolant from the fuel cell **2138** heats the liquid desiccant stream thereby driving water from the liquid desiccant stream in the mass transfer ducts **2116**C into the removal stream passing through the moisture removal duct **2106**C. The high humidity water recovery stream **2011** can be fed into a radiator to precipitate and capture the moisture in the water recovery stream **2011**.

[0136] In some embodiments, the regeneration system **2140** includes a third heat/mass transfer device **2100**C as described herein. In such embodiments, an outlet **2120**A of the first mass transfer duct system **2104**A is in fluid communication with an inlet **2118**C of the third mass transfer duct system **2104**C, and an outlet **2120**C of the third mass transfer duct system **2104**C is in fluid communication with an inlet **2118**A of the first mass transfer duct system **2104**A. In some embodiments, the warm exhaust from the fuel cell **2138** is fed into an inlet of the third air transport duct **2106**C, and warm heat transfer fluid (e.g., hot water) from the fuel cell **2138** is fed into an inlet **2112**C of the third heat transfer duct system **2102**C. Examples of such embodiments are shown in FIGS. **11-14**.

[0137] As shown in FIGS. **11-14**, the high concentration liquid desiccant exiting the third desiccant exhaust chamber **2120**C is then fed into a heat exchanger intended to cool the high concentration liquid desiccant stream before it is fed into the first desiccant header chamber **2118**A. In FIGS. **11-13**, the heat exchanger is a radiator used using a fan and ambient air to cool the cooled, humidified fuel cell exhaust stream exiting the third air transport duct **2106**C and the high concentration liquid desiccant exiting the third desiccant exhaust chamber **2120**C. In FIG. **14**, the heat exchanger is a fourth heat and mass exchange unit **2100**D that has been modified to use impermeable mass transfer ducts **2116**D, so that there is no mass exchange. Rather, the air flowing through the air transport duct **2106**D is used to cool both the humid fuel cell exhaust stream flowing through the heat transfer ducts **2110**D and the high-concentration liquid desiccant stream in the mass transfer ducts **2116**D (which have been modified so they are not mass transfer ducts).

[0138] A first specific heat and mass transfer device can include a heat transfer duct system; a mass transfer duct system; and an air transport duct, wherein portions of said heat transfer duct system and said mass transfer duct system extend through said air transport duct, wherein the mass transfer duct system comprises a water vapor permeable wall.

[0139] A second HMX device includes the first HMX device wherein said heat transfer duct system comprises a plurality of heat transfer ducts in fluid communication with a heat transfer fluid header chamber on one end and a heat transfer fluid exhaust chamber at an opposite end of the heat transfer ducts.

[0140] A third HMX device includes any of the foregoing HMX devices, wherein the mass transfer duct system comprises a plurality of mass transfer ducts in fluid communications with a desiccant header chamber on one end and a desiccant exhaust chamber at an opposite end of the mass transfer ducts.

[0141] A fourth HMX device includes the third HMX device, wherein said heat transfer duct system comprises a plurality of heat transfer ducts in fluid communication with a heat transfer fluid header chamber on one end and a heat transfer fluid exhaust chamber at an opposite end of the heat transfer ducts.

[0142] A fifth HMX device includes the fourth HMX device, wherein said plurality of mass transfer ducts are spaced apart from and interspersed with and said plurality of heat transfer ducts.

[0143] A sixth HMX device includes the fourth HMX device, wherein each heat transfer duct is positioned within a mass transfer duct, and wherein said mass transfer ducts are spaced apart from one another.

[0144] A seventh HMX device includes the sixth HMX device, wherein one, heat transfer duct is positioned coaxially within each mass transfer duct.

[0145] A eighth HMX device includes the sixth HMX device, wherein walls of said heat transfer ducts comprise a material selected from the group consisting of polyvinylidene dithioride (PVDF), polypropylene (PP), polyvinyl chloride (PVC), polyphenylene sulfide (PPS), polyethersulfone (PES), polytetrafluoroethylene (PTFE), and combinations thereof.

[0146] A ninth HMX device includes the fourth HMX device wherein each heat transfer duct is longer than each mass transfer duct.

[0147] A tenth HMX device includes the ninth HMX device, wherein a first end of each heat transfer duct is mounted to an opening in a heat transfer header plate, and an opposite end of each heat transfer duct is mounted to an opening in a heat transfer exhaust plate; wherein a first end of each mass transfer duct is mounted to an opening in a mass transfer header plate, and an opposite end of each mass transfer duct is mounted to an opening in a mass transfer exhaust plate; wherein at least a portion of said desiccant header chamber is between said heat transfer header plate and said mass transfer header plate; and wherein at least a portion of said desiccant exhaust chamber is between said heat transfer exhaust plate and said mass transfer exhaust plate.

[0148] A eleventh HMX device includes the fourth HMX device, wherein each mass transfer duct is longer than each heat transfer duct.

[0149] A twelfth HMX device includes any of the foregoing HMX devices, wherein no mass exchange occurs between said heat transfer duct system and said mass transfer duct system.

[0150] A thirteenth HMX device includes any of the foregoing HMX devices, wherein said mass transfer duct system comprises a wall formed from a material selected from the group consisting of a microporous plastic, structural porous duct covered with a microporous plastic, a structural porous duct covered with a water permeable polymer electrolyte membrane, or a combination thereof.

[0151] A fourteenth HMX device includes any of the foregoing HMX devices, wherein contents of the heat transfer duct system are in thermal communication with contents of the air transport duct via a wall, wherein said wall comprises a material selected from the group consisting of polyvinylidene difluoride (PVDF), polypropylene (PP), polyvinyl chloride (PVC), polyphenylene sulfide (PPS), polytetrafluoroethylene (PTFE), metal, and combinations thereof.

[0152] A fifteenth HMX device includes any of the foregoing HMX devices, wherein an inlet of said heat transfer duct is in fluid communication with a heat transfer fluid stream.

[0153] A sixteenth HMX device includes the fifteenth HMX device, wherein the heat transfer fluid stream comprises a heat transfer fluid selected from the group consisting of air, ethylene glycol, propylene glycol, glycerol, water, ammonia, fluorocarbons, chlorofluorocarbons, sulfur dioxide, halons, hydrocarbons, and mixtures thereof.

[0154] A seventeenth HMX device includes any of the foregoing HMX devices, wherein a liquid desiccant stream is fed into an inlet of said mass transfer duct system.

[0155] An eighteenth HMX device includes the seventeenth HMX device, wherein a desiccant concentration of the liquid desiccant stream is lower at an exit of the mass transfer duct system than at the inlet of the mass transfer duct system.

[0156] A first air conditioning system includes first and second HMX devices according to any of the foregoing HMX devices, wherein an exhaust of the first air transport duct is in fluid communication with an inlet to the second heat transfer duct system.

[0157] A second air conditioning system that includes the first air conditioning system, wherein air flowing through the second air transport duct undergoes evaporative cooling by a liquid stream containing water flowing in the mass transfer duct.

[0158] A third air conditioning system that includes any of the foregoing air conditioning systems, wherein:

- **[0159]** a first heat transfer fluid stream is fed into the first heat transfer duct system;
- **[0160]** a high concentration liquid desiccant stream is fed into the first mass transfer duct system;
- **[0161]** air being conditioned is fed into the first air transport duct;
- **[0162]** dehumidified air exiting the first air transport duct is fed into the second heat transfer duct system;
- **[0163]** a stream containing water is fed into the second mass transfer duct system; and
- **[0164]** secondary air is fed into the second air transport duct,

[0165] wherein the second mass transfer duct system comprises a wall comprising a mass transfer membrane that allows liquid water to pass, and wherein said secondary air undergoes evaporative cooling by water passing through the mass transfer membrane.

[0166] A fourth air conditioning system that includes the third air conditioning system, wherein the first heat transfer fluid stream comprises air.

[0167] A fifth air conditioning system that includes any of the foregoing air conditioning systems, wherein an exhaust stream from the second heat transfer duct system comprises dehumidified, cooled air that is supplied to a space being air conditioned.

[0168] A sixth air conditioning system that includes any of the foregoing air conditioning systems, wherein a low concentration liquid desiccant stream exiting said first mass transfer duct system is regenerated to produce a high concentration liquid desiccant stream fed into an inlet of the first mass transfer duct system.

[0169] A seventh air conditioning system that includes any of the foregoing air conditioning systems, further comprising a fuel cell, wherein warm heat transfer fluid from the fuel cell is used to regenerate the liquid desiccant stream by driving water out of the liquid desiccant stream.

[0170] An eighth air conditioning system that includes the sixth air conditioning system, further comprising a regeneration system, comprising: a moisture removal duct; and a desiccant regeneration duct extends through said moisture removal duct, wherein water vapor from the liquid desiccant stream in said desiccant regeneration duct selectively passes through a desiccant regeneration duct membrane into the moisture removal duct.

[0171] A ninth air conditioning system that includes the sixth air conditioning system, wherein warm heat transfer fluid from the fuel cell heats the liquid desiccant stream thereby driving water from the liquid desiccant stream into the fuel cell exhaust stream passing through the moisture removal duct.

[0172] A tenth air conditioning system that includes the ninth air conditioning system, wherein the regeneration system comprises a third HMX device according to any of the foregoing specific HMX devices, wherein an outlet of the first mass transfer duct system is in fluid communication with an inlet of the third mass transfer duct system, and an outlet of the third mass transfer duct system is in fluid communication with an inlet of the first mass transfer duct system.

[0173] An eleventh air conditioning system that includes the tenth air conditioning system, wherein the warm exhaust from the fuel cell is fed into an inlet of the third air transport duct, and warm heat transfer fluid from the fuel cell is fed into an inlet of the third heat transfer duct system.

Second Discussion

[0174] Described herein are methods and designs for a system where the heat exhausted from an engine is used to heat a liquid desiccant and/or an air stream, the latter referred as carrier air in this document. The carrier air is heated so that the partial pressure of the water vapor contained in the carrier air is lower than the concentration of water in a liquid desiccant stream that will be regenerated. The interaction between the liquid desiccant and the carrier air is accomplished through a membrane that is permeable to water vapor but not to the transfer of liquids, such as the liquid desiccant or liquid water. Given the difference in water concentration between the carrier air and the liquid desiccant, water flows from the liquid desiccant to the carrier air in the form of water vapor.

[0175] The process of liquid desiccant regeneration is continuously heated by a hot coolant stream proceeding from the engine that carries part or all of the heat produced by the engine. The hot coolant can in the form of a gas or a liquid. In some embodiments, the coolant can be a phase changing fluid in order to enhance heat transfer.

[0176] Desiccant regeneration occurs within a heat and mass transfer system (HMX) that enables heat transfer between the liquid desiccant, the coolant, and the carrier gas. It also enables exchange of water vapor between the liquid desiccant and the carrier air. The HMX is composed of a plurality of tubes over which carrier gas flows in a counter-flow or cross flow manner. A certain group of the tubes flow liquid desiccant and another group of tubes flow coolant.

[0177] The outer wall of any of the tubes containing liquid desiccant described herein can be made of a material that is hydrophobic, impermeable to liquids, and permeable to water vapor. Such materials can be sulfonated tetrafluoroethylene based fluoropolymer-copolymer (Nafion™, sold by DuPont), water conducting fluoropolymers, and non-fluorinated proton conducting polymers such as NanoClear™, available from Dais Analytic, high density polyethelene, spunbond olefins, among others described herein. The tubes in which coolant flow continuously warm the air, maintaining its relative humidity low. The distribution of these tubes can be such that a greater concentration of tubes carrying coolant occurs in the HMX area closer to the inlet of the carrier air.

[0178] An alternative HMX design is one where there is a tube assembly composed of a tube or a plurality of tubes within a larger diameter tube. In this case coolant flows within the smaller diameter tubes in the tube assembly and liquid desiccant flows within the larger diameter tube, but not within the smaller diameter tubes. The wall of the inner, smaller diameter tubes is made of a material that allows for heat transfer between the coolant and the liquid desiccant, but does not allow for mixing of the liquid desiccant with the coolant. These tube are made of materials that are chemically compatible with the liquid desiccant. The outer wall of the tube assembly is composed of a material that is permeable to water vapor but not permeable to liquids. The HMX would be composed of a plurality of these tube assemblies. Carrier air flows around these tube assemblies in crossflow. The liquid desiccant and the coolant flow counter-flow with respect to each other.

[0179] There may be cases where the coolant flow is much higher than the carrier air flow, or in which due to design or pressure drop considerations, it is convenient for the coolant to flow on the outside of the HMX tubes or tube assemblies. In these cases, the HMX would be composed of a chamber with a plurality of tube assemblies. These tube assemblies would be composed of an outer tube in which one or more smaller diameter tubes are located within. These smaller diameter tubes flow carrier gas within them. The outer, larger diameter tube flows liquid desiccant. The walls of the smaller diameter tubes are made of a material that is permeable to water vapor but not permeable to the flow of liquids. The wall of the outer, larger diameter tube is made of a material that is chemically compatible with the liquid desiccant but that is impermeable to gas or liquid. In this way, the liquid desiccant and the coolant only have heat transfer interaction but no mixing occurs. This design is principally relevant for cases where the coolant is a gas.

[0180] An alternative case may occur, where the coolant may be too hot to flow next to the liquid desiccant. In this case the HMX tube assemblies are, as previously described, made of a larger diameter tube within which is at least a single smaller diameter tube. The carrier air flows within the larger diameter tube but not within the smaller diameter tubes. The liquid desiccant flows within the smaller diameter tubes. The wall of the smaller diameter tube is made of a material permeable to water vapor and not permeable to liquids. The wall of the outer diameter tube is made of a material that prevents mixing between the hot coolant and the carrier air, but allows for heat transfer between the carrier air and the hot coolant. By heating the carrier air directly, and indirectly heating the liquid desiccant, the liquid desiccant stream can be protected from elevated coolant temperatures that could lead to chemical deterioration of the liquid desiccant.

[0181] In order to maintain separation between the flows within the tubes, the HMX assembly uses headers. The HMX tubes have two distinct lengths. The different lengths enable introduction of liquid desiccant into tubes of a certain length and either coolant or carrier air (depending on design as discussed in the paragraphs above) into tubes of a different length. The header of the HMX has two chambers, one adjacent the other. The header chamber closest to the interior portion of the HMX has fluid connection with the interior portion of the shorter length tubes, but does not have fluid connection with the interior portion of longer length tubes. The header chamber farthest from the interior of the HMX is in fluid connection with the interior portion of the longer length tubes. The two header chambers are not in fluid connection with each other.

[0182] In an alternative HMX design, where the tube-in-tube assemblies are not employed, the header chambers are next to each other but not in fluid connection with each other.

[0183] Heat and mass transfer enhancements can be made to the HMX. In the case that the carrier air flows across the outside of the HMX tubes or tube assemblies, mass transfer between the air and the liquid desiccant can be enhanced by placing walls in the HMX so that the carrier air has to flow in a tortuous path. In this way the space velocity of the carrier air in the HMX can be varied enhancing mass transfer.

[0184] An alternative method of enhancing mass and heat transfer in the HMX would be through the addition of vertical features that block a portion of the carrier air flow through the HMX. In this way, vortices and turbulence can be accomplished. These features can be rods over which the carrier air must pass. The rods may have roughness or features to enhance the creation of vortices or turbulences. These features can also be used to create helical bulk flow of the carrier air through the HMX by acting as fins that direct flow.

[0185] The engine exhaust gas contains products of the oxidation of a fuel, which includes water. In the case the engine exhaust has a higher temperature than the carrier air entering the system, gas to gas heat exchanger is used to transfer heat from the engine exhaust to the carrier air. The carrier air then enters into the HMX. The gas to gas heat exchanger can be made of plates with triangular or corrugated sheets that form structural elements as well as flow channels. The corrugated sheets form channels that are perpendicular to the channels in the adjacent plates. The direction of the corrugations also block air flow into certain plates. This ensures the engine exhaust gas does not mix with the carrier air in the gas to gas heat exchanger. Other methods for gas to gas heat exchange known in the art can also be used.

[0186] The carrier air leaving the HMX is mixed with the engine exhaust gas leaving the gas to gas heat exchanger. A mixer can be used to reduce the pressure drop associated with the integration of the two flows. Leaving the mixer the combined gas is cooled in order to condense the air in the air stream. The condenser can use ambient air as the cooling fluid. Water condensed is collected in a water reservoir. The cool gas leaving the condenser is exhausted.

[0187] Instances may exist where carrier air and engine exhaust gas mixing is not practical due to flow rate disparity, pressure drop considerations, or chemical compatibility. In these cases, the carrier gas is independently condensed through an independent condenser. The carrier gas leaving the HMX also passes through an independent condenser. The water condensed from both the carrier air stream and from the engine exhaust gas is collected in a water reservoir.

[0188] The liquid desiccant, at a high concentration point, leaving the HMX is stored in a reservoir.

[0189] Compared to the state of the art, this invention offers many advantages. The invention not only regenerates the liquid desiccant but it also collects water produced from the engine and the water removed from the liquid desiccant during the regeneration process. Water recovery and accumulation is highly valuable. If the engine exhaust stream and the carrier air stream is devoid of toxic substances, the water collected could be used for human, agricultural, or livestock processes. Water can also be used to support air conditioning operation. Water can also be used to support engine processes, such as fuel processing or cooling.

[0190] The invention also prevents the mixture of liquid desiccant with other streams. Liquid desiccants are typically corrosive. Maintaining the liquid desiccant separate from other flows reduces the potential for corrosion of valves, tanks, ducting, etc.

[0191] The present invention will now be described more particularly, by way of example, with reference to the accompanying drawings, in which:

[0192] FIG. **16** shows an embodiment as described herein through a process diagram for the liquid desiccant regeneration system. As shown, low concentration liquid desiccant (**3002**) flows from a reservoir (**3001**) to the HMX (**3015**). The HMX (**3015**) also receives a hot coolant stream (**3006**) leaving an engine (**3005**). Carrier air (**3008**) is introduced to the system and flows through an air to air heat exchanger (**3021**) where it warmed. The warm carrier air (**3009**) is introduced into the HMX. The carrier air (**3008**) is warmed through heat exchange with engine exhaust (**3013**) leaving the engine (**3005**). Within the HMX (**3015**) the coolant provides the heat to support the transfer of water vapor from the liquid desiccant (**3002**) to the warm carrier air (**3009**). The streams leaving the HMX (**3015**) is humidified carrier air (**3010**), high concentration liquid desiccant (**3003**), and coolant (**3007**). The coolant (**3007**) returns to the engine. The high concentration liquid desiccant (**3003**) is stored in a reservoir (**3004**). Carrier air (**3010**) leaving the HMX (**3015**) is mixed with engine exhaust (**3014**) in a mixer (**3016**) designed to reduce pressure drop associated with the combination of the two streams. The combined flow (**3011**) is cooled in a condenser (**3017**) which is a heat exchanger cooled with outside air (**3018**) or any other fluid that is at a lower temperature than the combined flow (**3011**) leaving the mixer. The cooling of the combined flow (**3011**) condenses a portion of the water in the flow. This water condensed (**3019**) is stored in a water reservoir (**3020**). The combined flow (**3012**) leaving the condenser is exhausted.

[0193] FIG. **17** shows the same process as described in FIG. **16**, however in this case, the carrier air (**3010**) leaving the HMX (**3015**) is condensed in a separate heat exchanger in the condenser (**3017**). The engine exhaust (**3014**) leaving the air to air heat exchanger (**3021**) is also condensed in a separate heat exchanger in the condenser (**3017**). Each gas stream leaving the condenser (**3017**) has its own exhaust (**3012** and **3013**).

[0194] FIG. **18** shows an embodiment of the design of the HMX (**3015**) as described herein. The figure shows the internal portion of the HMX (**3150**) and its internal walls, in order to show its general geometry and construction. Carrier air (**3009**) enters the HMX (**3015**) and flow around tubes carrying coolant (**3027**) and tubes carrying liquid desiccant (**3028**). The walls of the tubes carrying liquid desiccant (**3028**) are made of material that is hydrophobic, permeable to water vapor, but not permeable to liquids. The tubes carrying coolant (**3027**) are longer than the tubes carrying liquid desiccant (**3028**). The liquid desiccant tube ends are sealed and attached to plates (**3032***a* and **3032***b*) at each end. The ends of the tubes carrying coolant (**3027**) are sealed and attached to plates (**3031***a* and **3031***b*). The different tube lengths form separate spaces (**3022***a*, **3022***b*, **3023***a* and **3023***b*) where liquid desiccant (**3003**) and coolant (**3006**) can be introduced into the HMX (**3015**).

[0195] FIG. **19** shows the HMX (**3015**) design using tube assemblies (**3024**). As in FIG. **18** carrier air (**3009**) flow across the tube assemblies (**3024**). The tube assemblies (**3024**) are composed of two different diameter tubes, the smaller one inside the other. The smaller diameter tube is longer than the larger diameter tube. The longer length tube is attached and sealed to the wall of the tube at its ends to two plates (**3031***a* and **3031***b*). Flow in and out of the tube is not restricted by the plates (**3031***a* and **3031***b*). These plates (**3031***a* and **3031***b*) form fluid barrier between the fluids entering and exiting the longer length tube in the tube assembly (**3024**). Plates (**3032***a* and **3032***b*) are attached to the ends of the shorter length tube in the tube assembly (**3024**) in such a way that they seal the wall of the tube to the plates (**3032***a* and **3032***b*) but do not restrict flow in an out of the tube.

[0196] FIG. **20** shows in greater detail the construction of the tube assembly (**3024**) in an HMX in a cross-sectional cutout view of the HMX. Hot coolant (**3006**) enters the HMX (**3015**) in the chamber (**3022***a*) created by an external header wall (**3033***a*) and the plate (**3031***a*) that is attached to wall (**3030**) of the longer length tubes of the tube assembly (**3024**). The hot coolant is able to flow into the longer length tube of the tube assembly (**3024**) and exit into the chamber (**3022***b*) form ed by the space between an external header wall (**3033***b*) and the plate (**3031***b*) attached to the tube wall (**3030**) at the other end of the longer length tube in the tube assembly (**3024**). The coolant (**3007**) exits the HMX (**3015**) through the chamber (**3022***b*). FIG. **19** shows a top down flow of hot coolant (**3006**), however this is arbitrary. The coolant (**3006**) flow could be bottom to top in the HMX (**3015**). Also, the orientation of the HMX (**3015**) can be any which way better suits the use of the invention for a certain application.

[0197] As shown in FIG. **20**, the low concentration liquid desiccant (**3002**) enters the HMX (**3015**) in through the chamber (**3023***b*) opposite the entry chamber (**3022***a*) of the hot coolant (**3006**). The entry chamber (**3023***b*) of the low concentration liquid desiccant (**3002**) is bound by the plate (**3031***b*) attached to the wall (**3030**) at the end of the longer length tube of the tube assembly (**3024**) and the plate attached to the plate (**3032***b*) attached to the wall (**3029**) of the shorter length tube of the tube assembly (**3024**). Liquid desiccant (**3002**) is able to flow around the outer wall (**3030**) of the longer length tube of the plate assembly (**3024**) but there is no fluid connection between the liquid desiccant stream (**3002** and **3003**) and the coolant streams (**3006** and **3007**). The liquid desiccant (**3002**) is able to flow in the annular space between the longer length tube and the shorter length tube of the tube assembly (**3024**). The outer wall (**3029**) of the shorter length tube of the tube assembly (**3014**) is entirely or partially composed of a hydrophobic material that is permeable to water vapor but not to liquids. Carrier air (**3009**) that enters the HMX (**3015**) picks up water vapor from the liquid desiccant (**3002**) as it flows around the tube assemblies (**3024**) in the HMX. The liquid desiccant leaves the HMX (**3015**) through a chamber (**3023***a*) that maintains separated the liquid desiccant stream (**3003**) and the coolant stream (**3006**). A plurality of these tube assemblies (**3024**) exist in the HMX (**3015**).

[0198] FIG. **21** shows a cross-section top view of a tube assembly (**3024**). Carrier air (**3009**) flows around the tube assembly (**3024**). The outermost wall (**3029**) of the tube assembly is made of a hydrophobic material permeable to water vapor but not permeable to liquids. Liquid desiccant (**3003**) flows out of the page (shown with a period to represent this) and within the annular compartment made by the wall (**3030**) of the innermost tube of the tube assembly (**3024**) and the outermost wall of the tube assembly (**3029**). Hot coolant (**3006**) flows into the page (shown as a plus sign to represent this), so the liquid desiccant (**3003**) and the hot coolant (**3006**) are in counterflow. The innermost wall (**3030**) of the tube assembly (**3024**) is made of a material that completely seals the coolant (**3006**) from the liquid desiccant (**3003**), but allows heat transfer between the two fluids.

[0199] FIG. **22** shows an alternative structure of the tube assembly (**3024**), where hot coolant (**3006**) flows across the outside of the tube assembly (**3024**). In this case outermost wall (**3030**) of the tube assembly (**3024**) is made of a material that allows heat transfer between the coolant (**3006**) and the liquid desiccant (**3003**). The liquid desiccant flows within the annular compartment bound by the outermost wall (**3030**) of the tube assembly (**3024**) and the innermost wall (**3029**) of the tube assembly. Carrier air (**3009**) flows within the innermost tube in the tube assembly (**3024**). The innermost wall (**3029**) of the tube assembly is made of a hydrophobic material that is permeable to water vapor but not to liquids.

[0200] FIG. **23** shows another alternative to the structure of the tube assembly (**3024**), where hot coolant (**3006**) flows across the outside of the tube assembly (**3024**). In this case outermost wall (**3030**) of the tube assembly (**3024**) is made of a material that allows heat transfer between the carrier air (**3009**) and the coolant (**3006**). The carrier air flows within the annular compartment hound by the outermost wall (**3030**) of the tube assembly (**3024**) and the innermost wall (**3029**) of the tube assembly. Liquid desiccant (**3003**) flows within the innermost tube in the tube assembly (**3024**). The innermost wall (**3029**) of the tube assembly is made of a hydrophobic material that is permeable to water vapor but not to liquids.

[0201] FIG. **24**A and FIG. **24**B show the HMX (**3015**) with heat and mass transfer enhancements between the carrier air (**3009**) and the tube assemblies (**3024**). Flow disrupters (**3034**) are place throughout the HMX in order to create turbulence and direct flow. The flow disrupters (**3034**) shown in this embodiment are cylindrical rods placed so that they run perpendicular to the direction of the tube assemblies (**3024**).

[0202] FIG. **25** shows the HMX (**3015**) with structural elements that cause the flow of the carrier air (**3009**) to be sinusoidal throughout the HMX (**3015**). This increases reactor effective length.

[0203] A first liquid desiccant regeneration system can include a heat and mass exchanger, comprising: a plurality of exchange components extending across a heat and mass exchanger duct, wherein a flow through said heat and mass exchanger duct is cross-flow relative to said exchange components, wherein said exchange components comprise a plurality of first elongated, hollow conduits and a plurality of second elongated, hollow conduit; and an engine producing an exhaust stream and a coolant stream, wherein said exhaust stream is in thermal communication with a carrier air stream subsequently fed into the heat and mass exchanger, wherein said heat and mass exchanger receives a liquid desiccant stream, the coolant stream, and a carrier air stream, wherein one of said first and second elongated, hollow conduits comprises a water vapor permeable tube wall, and wherein the liquid desiccant stream and the carrier air stream are in contact with said water vapor permeable tube wall.

[0204] A second desiccant regeneration system according to the first desiccant regeneration system, wherein said each of said first and second elongated, hollow conduits is spaced apart from the other.

[0205] A third desiccant regeneration system according to the second desiccant regeneration system, wherein said first elongated, hollow conduits extend laterally across said heat and mass exchanger duct and said second elongated, hollow conduits extend transverse to said first elongated, hollow conduits.

[0206] A fourth desiccant regeneration system according to the second desiccant regeneration system, wherein each of said first elongated, hollow conduits is an outer conduit of a tube-in-tube exchanger component, each of said tube-in-tube exchanger components further comprising an inner conduit, wherein an inner lumen is defined by said inner conduit and an outer flow channel is external to said inner conduit and adjacent a wall of said second elongated, hollow conduit.

[0207] A fifth desiccant regeneration system according to any of the foregoing desiccant regeneration systems, wherein said exchange components comprise tube-in-tube exchange components, wherein each tube-in-tube components comprises one first elongated, hollow conduit within one second elongated, hollow conduit, forming an inner lumen within said first elongated, hollow conduit and an outer flow channel external to said first elongated, hollow conduit and adjacent a wall of said second elongated, hollow conduit.

[0208] A sixth desiccant regeneration system according to the fifth desiccant regeneration system, wherein said coolant stream flows through said central lumen, said liquid desiccant stream flows through said sheath, and said carrier air stream flows through said heat and mass exchanger duct.

[0209] A seventh desiccant regeneration system according to the sixth desiccant regeneration system, wherein the coolant stream and the liquid desiccant stream are configured in a counter flow arrangement.

[0210] A eighth desiccant regeneration system according to the fifth desiccant regeneration system, wherein said carrier air stream flows through said central lumen, said liquid desiccant stream flows through said sheath, and said coolant stream flows through said heat and mass exchanger duct,

[0211] A ninth desiccant regeneration system according to the eighth desiccant regeneration system, wherein the carrier air stream and the liquid desiccant stream are configured in a counter flow arrangement.

[0212] A tenth desiccant regeneration system according to the fifth desiccant regeneration system, wherein said liquid desiccant stream flows through said central lumen, said carrier air stream flows through said sheath, and said coolant stream flows through said heat and mass exchanger duct.

[0213] An eleventh desiccant regeneration system according to the tenth desiccant regeneration system, wherein the liquid desiccant stream and the carrier air stream are configured in a counter flow arrangement.

[0214] A twelfth desiccant regeneration system according to any of the foregoing desiccant regeneration systems, wherein the carrier air stream exiting the heat and mass exchanger passes through a condenser, wherein a water trap of said condenser is in fluid communication with a reservoir.

[0215] A thirteenth desiccant regeneration system according to any of the foregoing desiccant regeneration systems, wherein, after thermally contacting the carrier air stream, the exhaust stream passes through a condenser, wherein a water trap of said condenser is in fluid communication with a reservoir.

[0216] A fourteenth desiccant regeneration system according to the thirteenth desiccant regeneration system, wherein, the carrier air stream exiting the heat and mass exchanger is mixed with the exhaust stream to form a combined air stream and the combined air stream passes through a condenser.

[0217] A fifteenth desiccant regeneration system according to any of the foregoing desiccant regeneration systems, wherein a low concentration liquid desiccant reservoir is in fluid communication with a high concentration liquid desiccant reservoir via the liquid desiccant stream.

[0218] A sixteenth desiccant regeneration system according to any of the foregoing desiccant regeneration systems, wherein, after passing through the heat and mass exchanger, the coolant stream is reintroduced into the engine.

[0219] A seventeenth desiccant regeneration system according to any of the foregoing desiccant regeneration systems, further comprising a plurality of flow disrupters extending from at least one wall of said heat and mass exchanger duct.

[0220] An eighteenth desiccant regeneration system according to the seventeenth desiccant regeneration system, wherein the flow disrupters extend across said heat and mass exchanger duct.

[0221] A nineteenth desiccant regeneration system according to the seventeenth desiccant regeneration system, wherein said flow disrupters have a cross-sectional shape selected from the group consisting of airfoils, triangles, rectangles, and others.

[0222] A twentieth desiccant regeneration system according to the seventeenth desiccant regeneration system, wherein said heat and mass exchanger duct comprises first and second longitudinal walls opposite one another, and said flow disrupters comprise at least one first fin extending from the first longitudinal wall partially across said heat and mass exchanger duct and at least one second fin extending from the second longitudinal wall partially across said heat and mass exchanger duct.

[0223] A twenty-first desiccant regeneration system according to the twentieth desiccant regeneration system, wherein said flow disruptors cause flow through said heat and mass exchanger duct to travel in an s-shaped path.

[0224] A twenty-second desiccant regeneration system according to any of the fifth through twenty-first desiccant regeneration systems, wherein at least one of said tube-in-tube exchange components comprises a flow disrupter.

[0225] A twenty-third desiccant regeneration system according to any of the foregoing desiccant regeneration systems, wherein said exhaust stream is contacted with said carrier air stream via a heat exchanger.

[0226] A twenty-fourth desiccant regeneration system according to any of the fifth through twenty-third desiccant regeneration systems, wherein each of said tube-in-tube exchanger components further comprises an intermediate elongated, hollow conduit, wherein the outer flow channel is defined between an outer wall of said intermediate elongated, hollow conduit and said second elongated, hollow conduit, and an intermediate flow channel is defined between said first elongated, hollow conduit and said intermediate elongated, hollow conduit.

Third Discussion

[0227] The dehumidifier system described herein uses hygroscopic liquids including, but not limited to salt solutions (e.g., LiCl, NaCl, $CaCl_2$), alcohols (e.g., glycerol, methanol, ethanol), chemical agents (e.g., $CaSO_4$) or combinations thereof, to dehumidify an incoming air stream for air conditioning purposes. The design of the dehumidifier is such that heat energy is continually being removed throughout the dehumidification process by means of, but not necessarily exclusively by, air flow from the atmosphere, air subjected to evaporative cooling, or a liquid coolant such as water. This removal of heat, specifically from the liquid desiccant, is advantageous for promoting continued air dehumidification as the liquid desiccant concentration is reduced due to the absorption of water vapor.

[0228] Described herein are methods and designs for dehumidification and cooling of air using a water vapor-permeable tube to separate the liquid desiccant from the air stream and one or more water vapor-impermeable tubes to separate the air stream from the coolant and to separate the liquid desiccant from the coolant. In some of these embodiments, ambient, humid air is dehumidified as it passes perpendicular to the axes of a plurality of parallel water vapor-permeable tubes into which liquid desiccant is introduced. Alternative approaches are provided with respect to the manner in which a coolant (such as ambient air), or another coolant such as water, glycol or other suitable fluid (e.g., gas or liquid) is used to cool the liquid desiccant as it absorbs water.

[0229] Compared to the state of the art, the devices described herein more effectively make use of water vapor-permeable materials in order to prohibit carry-over of the liquid desiccant to the dehumidified air. Specifically, the devices and systems use membrane tubes, in conjunction with structural supporting tubes and structural supporting manifold reservoirs, to provide the desired fluid separation as well as a more robust and reliable manner to seal and convey or circulate the liquid desiccant. The described device design enables the use of various methods for securing and sealing the tubes to the manifold reservoirs, including o-rings, plastic welding, chemical bonding, compression fittings and other assembly components and methods known to one versed in the art. Suitable materials for the tubes, manifold reservoirs, water vapor-permeable tubes and other wetted components include, but are not limited to PVDP, PP, HDPE, PVC, PPS, PES, PTFE and other polymers. Solid electrolyte membranes are also appropriate for selectively transporting water in the device. These membranes include sulfonated tetrafluoroethylene based fluoropolymer-copolymer (Nafion™, sold by DuPont), water conducting fluoropolymers, and non-fluorinated proton conducting polymers such as NanoClear™, available from Dais Analytic.

[0230] The devices and systems described herein offer advantages in design flexibility and expandability due to the use of repeating tube elements and simplicity of construction. It provides advantages in controllability due to the fact that air and liquid desiccant flow rates may be changed as needed to meet operator preferences of humidity and temperature, or based on varying ambient conditions, without concern for the entrainment of liquid desiccant in the air and corrosion of vulnerable downstream components. The device offers functional versatility in that it may be used to provide indirect cooling of an air stream through the evaporative cooling of a secondary air stream that is exposed to water, rather than liquid desiccant. The design also supports the use of multiple heal and/or mass transfer fluids by simply increasing the number of manifold reservoir connection surfaces and diameters and lengths of the tubes.

[0231] The device will now be described more particularly, by way of example, with reference to the accompanying drawings, in which:

[0232] FIG. **26** shows a cross-sectional view of the arrangement of heat and mass transfer tubes in an embodiment of the heat and mass transfer device **4100**. Shown are two stages used to dehumidify a supply air stream **4005**, and then cool the dehumidified air stream **4006** to produce cool, dry air **4007**. In the dehumidification stage **4200**, a supply air stream **4005** is passed across the surface of a water vapor-permeable mass transfer tube **4202** that contains a stream of liquid desiccant **4204**. Water vapor is absorbed by the liquid desiccant **4204**, which tends to increase in temperature due to the heat of condensation of the water vapor. A temperature increase of the liquid desiccant **4204** adversely affects its ability to absorb water vapor, so a coolant **4203** such as water is introduced into a heat transfer tube **4201** concentrically located within the mass transfer tube **4202**. Exhaust air **4209**, such as air being removed from an air conditioned building, is also introduced into the heat transfer tube **4201** in order to reduce the temperature of the liquid desiccant **4204** through the process of indirect evaporative cooling. The heat transfer tube **4201** may incorporate a layer of hydrophilic material **4211** in order to produce a more uniform film of water on the internal surface of the heat transfer tube **4201**, thereby increasing surface area and providing greater evaporative cooling effect. In the cooling stage **4300**, the dehumidified air stream **4006** is passed across the surface of a water vapo-impermeable heat transfer tube **4301** into which a coolant **4303** such as water is introduced. As in the dehumidification stage **4200**, exhaust air **4309** is also introduced into the heat transfer tube **4301** in order to cool the dehumidified supply air **4006** through indirect evaporative cooling. The heat transfer tube **4301** of the cooling stage **4300** may also incorporate a layer of hydrophilic material **4311** in order to produce a more uniform film of water on the internal surface of the heat transfer tube **4301**, thereby increasing surface area and providing greater evaporative cooling effect. Not shown are three additional variants of FIG. **26** in which:

[0233] a. Supply air **4005** is introduced into a mass transfer tube **4202** concentrically located within the heat transfer tube **4201** of the dehumidification stage **4200**. An exhaust air stream **4209** and coolant **4203** are passed across the surface of the heat transfer tube **4201**. The heat transfer tube **4201** may incorporate a layer of hydrophilic material **4211** in order to produce a more uniform film of water on the external surface of the heat transfer tube **4201**, thereby increasing surface area and providing greater evaporative cooling effect. Liquid desiccant **4204** is contained by the heat transfer tube **4201** and mass transfer tube **4202**, as in FIG. **26** and no changes in the fluid arrangement are made to the cooling stage **4300**.

[0234] b. Dehumidified supply air **4006** is introduced into the heat transfer tube **4301** of the cooling stage **4300**. An exhaust air stream **4309** and coolant **4303** are passed across the surface of the heat transfer tube **4301**. The heat transfer tube **4301** may incorporate a layer of hydrophilic material **4311** in order to produce a more uniform film of water on the external surface of the heat transfer tube **4301**, thereby increasing surface area and providing greater evaporative cooling effect. No changes in the fluid arrangement are made to the dehumidification stage **4200**.

[0235] c. Changes in the fluid arrangement of the dehumidification stage **4200** and of the cooling stage **4300** described in a) and b), above, are both employed.

[0236] FIG. **27** shows a model of an embodiment of the dehumidification stage **4200** of the heat and mass transfer device **4100** described by FIG. **26** with distinct and concentric heat transfer tubes **4201** and mass transfer tubes **4202**. FIG. **28** shows a section view of FIG. **27**. In this embodiment, the heat transfer tubes **4201** are concentric and internal to larger diameter mass transfer tubes **4202**. The mass transfer tubes **4202** are retained by and sealed against two first surfaces of an inlet manifold reservoir **4221** and an outlet manifold reservoir **4222**. Longer heat transfer tubes **4201** are retained by and sealed against two second surfaces of the inlet manifold reservoir **4221** and outlet manifold reservoir **4222**. This arrangement leaves a gap between the outer diameter of the smaller heat transfer tubes **4201** and the inner diameter of the larger mass transfer tubes **4202** into which the liquid desiccant **4204** may flow when introduced into the inlet manifold reservoir **4221** at inlet connection **4223**. The air to be dehumidified **4005** passes perpendicular to the axes of the mass transfer tubes **4202**. Dehumidified air **4006** exits the device after it passes by the plurality of mass transfer tubes **4202**. As water vapor in the supply air **4005** is absorbed by the liquid desiccant **4204**, the temperature of the liquid desiccant **4204** in the mass transfer tubes **4202** tends to increase. A coolant **4203** is introduced into the smaller, interior heat transfer tubes **4201**, which reduces the magnitude of temperature increase of the liquid desiccant **4204**, with which it is in thermal contact. The heat transfer tubes **4201** may be made entirely of a compatible material, not subject to corrosion by the liquid desiccant **4204**, or they may be constructed from aluminum or another material with high thermal conductivity, and then coated with a suitable harrier including PP, HDPE, PPS, PVC, PTFE, and PVDF, among others. In any case, thin-walled tubing is desirable for improved heat transfer from the liquid desiccant **4204** to the coolant **4203**. Other methods to increase heat transfer may also be used, such as fins, wall corrugations and features that increase fluid turbulence and heat transfer area.

[0237] The section view in FIG. **28** defines three duct systems or ducts for an embodiment of the dehumidification stage **4200** of the heat and mass transfer device **4100**:

[0238] 1) The heat transfer duct system is defined by the walls of the heat transfer tubes **4201** and the outer surfaces of the inlet and outlet manifold reservoirs **4221** and **4222** that face away from each other and which position and seal against the heat transfer tubes **4201**.

[0239] 2) The mass transfer duct system is defined by the walls of the mass transfer tubes **4202**, the walls of the heat transfer tubes **4201**, and the walls of the inlet and outlet manifold reservoirs **4221** and **4222**, leading from the inlet connection **4223** to the outlet connection **4224**.

[0240] 3) The air duct is defined by the surfaces of the inlet and outlet manifold reservoirs **4221** and **4222** that face each other and position and seal against the mass transfer tubes **4202**.

[0241] FIGS. **29** and **30** show a model and section view of the cooling stage **4300**. In this stage of the heat and mass transfer device **4100**, holes are provided in the manifold reservoirs **4321** and **4322** only for connection and sealing of heat transfer tubes **4301**; mass transfer tubes are not utilized in this embodiment. As described by FIG. **26**, dehumidified supply air **4006** passes across the surfaces of the heat transfer tubes **4301** and exits as dehumidified and cooled air **4007**. In an embodiment, the coolant **4303** and exhaust air stream **4309** are introduced into an opening that approximates the entire second surface area of the inlet manifold reservoir **4321**. This reduces pressure drop that would otherwise be associated with use of small inlet and outlet connections and improves flow uniformity in the plurality of heat transfer tubes **4301**. The heat transfer tube **4301** may incorporate a layer of hydrophilic material **4311** in order to produce a more uniform film of water on the internal surface of the heat transfer tube **4301**, thereby increasing surface area and providing greater evaporative cooling effect.

[0242] FIG. **31** shows an embodiment of a two-stage heat and mass transfer device **4100** in which the dehumidification stage **4200** and the cooling stage **4300** are packaged with their respective tube assemblies oriented perpendicular to each other and transverse with respect to the duct in which supply air **4005** is introduced. The use of staggered tube placement and alternating mass transfer tubes **4202** and heat transfer tubes **4301** provides benefits including increased turbulence of the supply air **4005** for improved heat and mass transfer, and a more compact design than other embodiments that use a series arrangement of a distinct dehumidification stage **4200** and cooling stage **4300**, in the dehumidification stage **4200**, the liquid desiccant stream **4204** and coolant stream **4203** are shown in a counter-flow arrangement. In the cooling stage **4300**, the coolant stream **4303** and exhaust air stream **4309** are also shown in a counter-flow arrangement, which allows for increased exposure of the coolant **4303** to the exhaust air stream **4309** and leads to greater indirect evaporative cooling of the increasingly dehumidified air **4006** from each successive set of mass transfer tubes **4202**.

[0243] FIG. **32** shows an embodiment of a two-stage heat and mass transfer device **4100** in which a liquid such as cold water is the coolant **4203** and **4303** and no exhaust air **4209** or **4309** is used in the heat and mass transfer device **4100**. Instead, water may be cooled by a cooling tower or it may be otherwise available to be pumped to the heat and mass transfer device **4100**. In this manner, the coolant **4203** reduces the temperature of the liquid desiccant **4204** in the dehumidification stage **4200** and the coolant **4303** cools the dehumidified air stream **4006** in the cooling stage **4300** in order to produce dehumidified and cooled air **4007**. The use of a liquid coolant offers advantages including, but not limited to increased design flexibility with respect to tube diameters and lengths, which may allow for more compact designs.

[0244] FIG. **33** and FIG. **34** show a diagram and model of an embodiment of a one-stage heat and mass transfer device **4100**. The liquid desiccant stream **4404** is contained and separated from the supply air stream **4005** by a water vapor permeable mass transfer tube **4402**. A first heat transfer tube **4401** is concentrically located within the liquid desiccant stream **4404** and the supply air stream **4005**; a second heat transfer tube **4501** is concentrically located outside the liquid desiccant stream **4404** and the supply air stream **4005**. A coolant **4403** such as water is introduced into the first heat transfer tube **4401** and a coolant **4503** is applied by spraying Of other means onto the outside of the second heat transfer tube **4501**. The first heat transfer tube **4401** and second heat transfer tube **4501** may each incorporate a layer of hydrophilic material **4411** and **4511** in order to produce a more uniform film of water on the internal surface of the first heat transfer tube **4401**, and the external surface of the second heat transfer tube **4501**, thereby increasing surface area and providing greater evaporative cooling effect. In this and other one-stage embodiments of the heat and mass transfer device **4100** the supply air stream **4005** may exhibit undesirable pressure drop and flow non-uniformity at the inlet and outlet manifold reservoirs **4421** and **4422** and along the gaps generated between the plurality of heat transfer tubes **4201** and **4301** and mass transfer tubes **4202**. One skilled in the art may reduce these undesirable effects with the use of larger inlet and outlet connections for the supply air stream **4005**, deeper manifold reservoirs **4421** and **4422** in which the supply air **4005** flow may become organized, and a balance between turbulence-inducing features and adequate hydraulic diameter. Not shown is another embodiment of FIG. **33** and FIG. **34** in which the location of the supply air stream **4005** and the liquid desiccant stream **4404** is reversed, such that the liquid desiccant **4404** flows adjacent to the outer heat transfer tube **4501** and the supply air **4005** flows adjacent to the inner heat transfer tube **4401**.

[0245] FIG. **36** shows another embodiment of a one-stage heat and mass transfer device **4100** that uses a liquid such as cold water as the coolant **4403** and **4503**, and no exhaust air stream is used locally within the heat and mass transfer device **4100**. Instead, cold water may be produced remotely by a cooling tower by evaporative cooling with the exhaust air stream or it may be otherwise available to be pumped to the heat and mass transfer device **4100**. The use of a liquid coolant offers advantages including, but not limited to increased design flexibility with respect to tube diameters and lengths, which may allow for more compact designs.

[0246] FIG. **37** shows an embodiment of a one-stage heat and mass transfer device **4100** that uses only one heat transfer tube **4501**. The supply air stream **5** is cooled via indirect evaporative cooling with the coolant **4503** and the exhaust stream **4509**, or with just a liquid coolant **4503** such as water. The heat transfer tube **4501** may incorporate a layer of hydrophilic material **4511** in order to produce a more uniform film of water on the outer surface of the heat transfer tube **4501**, thereby increasing surface area and providing greater evaporative cooling effect. Some instances, such as when the liquid desiccant **4404** flow rate and turbulence is sufficiently high, allow for removal of heat from the interface film at the surface of the heat transfer tube **4501**. This may provide the opportunity to eliminate the coolant stream that would otherwise be used to cool the liquid desiccant stream **4404** through a heat transfer tube located concentrically within the mass transfer tube **4402**, leading to simplification of construction of the heat and mass transfer device **4100**.

[0247] FIG. **38** shows a coupling device **4050** used to position and seal two concentric tubes and FIG. **39** shows a model of a heat and mass transfer tube subassembly **4060**. In one embodiment, the coupling devices **4050** and **4051** are sealed by thermal welding or other methods to the heat transfer tube **4201** and to the mass transfer tube **4202**, thereby creating a tube subassembly **4060** and facilitating assembly of the heat and mass transfer device **4100**. Features at the inner and outer diameters of the coupling devices **4050** and **4051** provide sealing surfaces, against which the mass transfer tube **4202**, heat transfer tube **4201** and manifold reservoirs **4221** and **4222** may be joined. A plurality of through-passages are located in a circular array in between the coupling device **4051** surfaces to which are joined the outer diameter of the heat transfer tube **4201** and the inner diameter of the mass transfer tube **4202**. These through-passages allow for the conveyance of liquid desiccant **4204** into the gap between the heat transfer tubes **4201** and the mass transfer tubes **4202**. Increased heat transfer between the liquid desiccant **4204** and the coolant **4203**, and between the liquid desiccant **4204** and the supply air stream **4005** may be accomplished by directing the through-holes at an angle, such as 45° from an axis parallel to the axis of the coupling devices **4050** and **4051**. The use of these angled through-hole features and other swirl-inducing features increases the flow path length of the liquid desiccant **4204** and increases the time with which the liquid desiccant is in contact with the supply air stream **4005**, thereby increasing the amount of water vapor the liquid desiccant **4204** absorbs. The coupling devices **4050** and **4051** may be made from a material such as PP, HDPE, PVC, or other plastics that are suitable for exposure to the corrosive liquid desiccant **4204**. Methods for joining the heat transfer tube **4201** and mass transfer tube **4202** to the coupling devices **4050** and **4051** include, but are not limited to thermal welding, but other methods including chemical welding and adhesives may also be used.

[0248] FIG. **40** shows a detail view of an embodiment of the tube subassembly **4060** sealed at the coupling device **4050** to the manifold reservoirs **4221** and **4222**. This may be accomplished by means of hot plate plastic welding, o-rings, or other techniques. When joined together with the manifold reservoirs **4221** and **4222**, the tube subassembly completes the sealed cooling duct system and the liquid desiccant duct system, and isolates the liquid desiccant **204** from the supply air stream **5**.

[0249] FIG. **35** shows a coupling device **4053** that is useful in producing heat and mass transfer tube subassemblies that may be used in the embodiments described in FIGS. **33**, **34**, and **36**. The coupling device **5053** provides passages for conveying liquid desiccant **4404**, coolant **4403**, exhaust air **4409** and supply air **4005**, as shown in FIG. **34**. It also provides sealing surfaces for joining to heat transfer tubes **4401** and **4501**, mass transfer tube **4402**, and to the manifold reservoir **4421** shown in FIG. **34**.

[0250] FIG. **5** shows a structural, porous support **4020** to which a water vapor permeable material may be thermally bonded or otherwise adhered to produce a mass transfer tube.

In a similar manner, water vapor impermeable material may be used in conjunction with a structural, porous support **4020** to produce a heat transfer tube. Extruded plastic tubes or tubes fabricated from plastic sheet material may be of a multitude of cross-sectional shapes that increase surface area, increase flow turbulence, or otherwise facilitate improved heat and mass transfer. The cross-sectional shape of the structure shown in FIG. **5**, which may be used for the heat transfer tube or mass transfer tube, is that of a foil, but it is understood that other shapes that increase surface area, increase flow turbulence or otherwise facilitate improved heat and mass transfer may be used. FIGS. **41** and **42** show two embodiments in which a foil-shaped mass transfer tube **4202** is utilized for a dehumidification stage **4200** such as is shown in FIGS. **26**, **27** and **28**.

[0251] In one embodiment, shown in FIG. **43**, a plurality of foil shaped mass transfer tubes **4202** containing liquid desiccant **4204** is used to increase the flow path length of the supply air **4005** in the duct in which the supply air **4005** is conveyed. This increased length allows more time for exposure of the supply air **4005** to increased surface area, of water vapor permeable mass transfer tubes **4202**, resulting in lower water vapor content in the dehumidified air stream **46**. The downstream element of FIG. **43** shows an embodiment in which dehumidified air **4006** is exposed to a plurality of foil shaped heat transfer tubes **4301**. The length of the flow path is increased in this manner, exposing the dehumidified air **4006** to greater heat transfer tube surface area over an increased duration, thereby providing for greater temperature reduction of the dehumidified and cooled air stream **4007**.

[0252] Some embodiments of the cooling stage **4300** may spray or otherwise apply a coolant **4303** such as water to the surface of foil or other shaped heat transfer tubes **4301** that convey dehumidified supply air **4006**. Exhaust air **4309** may be passed over the surface of the wetted heat transfer tubes **4301**. The heat transfer tube **4301** may incorporate a layer of hydrophilic material **4311** in order to produce a more uniform film of water on the external surface of the heat transfer tube **4301**, thereby increasing surface area and providing greater evaporative cooling effect. This method provides the exhaust air **4309** a greater amount of time to contact an increased volume of water, allowing it to reach equilibrium with the water, thereby maximizing the temperature reduction of the water and increasing the degree to which the dehumidified air stream **4006** is cooled. As indicated by the examples shown in FIGS. **42** and **42**, a foil or other shaped heat transfer tube **4201** may be used in the dehumidification stage **4200** of embodiments of the heat and mass transfer device **4100** for improved cooling of the supply air stream **4005** and the liquid desiccant stream **4204**.

[0253] As with the circular cross-section heat transfer tubes **4201** and **4301** and mass transfer tubes **4202** shown in FIG. **31**, a foil or other cross-sectional shape may be applied in a manner that produces vortices and increases turbulence in the air duct, thereby increasing the magnitude of heat and mass transfer and providing for more compact heat and mass transfer device designs.

[0254] Another method for increasing heat and mass transfer is to use helical features to increase the time that fluid streams on opposing sides of the tube wall have to reach equilibrium in temperature, or in water content. FIG. **44** shows an embodiment of a heat transfer tube **4201** that includes a helical barrier wall **4251** that induces a spiral flow path of the liquid desiccant **4204**. The resulting increased flow path length improves heat transfer from the liquid desiccant to the coolant **4203** and exhaust air **4209** that is introduced inside the heat transfer tube **4201**. FIG. **44** shows the profile of an extrusion **4250** that may be manufactured as flat stock and formed into a round tube. Adjacent edges of the extrusion are then bonded together by thermal welding or other methods, resulting in the water vapor impermeable heat transfer tube **4201** shown in FIG. **44**.

[0255] The mass transfer tube may be produced using various materials and methods that achieve the desired water vapor transport from the humid air to the liquid desiccant and provide chemical compatibility with the liquid desiccant. In order to contain the liquid desiccant in the mass transfer tube, a hydrophobic woven plastic or hydrophobic non-woven plastic including, but not limited to meltblown and spunbonded olefins, or microporous membranes with porosity including, but not limited to a range of 0.05 microns to 0.5 microns, may be used. The combination of small pores and a hydrophobic material prevents water from migrating through the aforementioned materials under normal operating conditions (e.g., pressures under 20 psi). However, when the pressure inside the tube is increased above a breakthrough pressure liquid water can seep through the pore structure.

[0256] As used herein, "breakthrough pressure" relates to the minimum pressure at which liquid water will cross a hydrophobic woven or non-woven material or hydrophobic microporous membrane that is only water-vapor permeable at lower pressures. For example, the breakthrough pressure of a hydrophobic sintered material with a porosity of 0.1 microns may be approximately 60 psi.

[0257] When operated at a breakthrough pressure, water will pass through to the surface of the hydrophobic material to produce a thin sheet of water around the surface. An alternate technique for producing a thin sheet of water on the surface of the tubes is utilizing a hydrophilic material at lower pressures. Mister spray-heads can be used to introduce water droplets for evaporative cooling anywhere herein where a hydrophobic material at a breakthrough pressure or a hydrophilic material is used. Humidification media such as Mufflers CELdek® may also be used in conjunction with water drip or mister spray heads to provide evaporative cooling of an exhaust air stream **4209**, **4309**, **4409**, and **4509** which may then be used as the coolant in any of the heat and mass transfer device **4100** embodiments described herein.

[0258] To promote water vapor transport, in some embodiments, a thickness of a microporous membrane includes, but is not limited to the range of 10 microns to 50 microns and its open area should exceed 50%. In some embodiments, the open area is greater than 70%. For the purpose of mechanically supporting this thin, microporous membrane, and to prohibit the collapse of the membrane tube in the case that the liquid desiccant is at a lower pressure than the surrounding ambient air, a structural, internal support tube **4020** can be provided. This design approach, with the microporous membrane covering the outside surface of the structural support tube **4020**, permits the liquid desiccant to be nearest to the passing air to be dehumidified, and promotes water vapor transport across the membrane. Both the structural tube **4020** and membrane may be produced from a suitable material such as PVDF, PP, HDPE, PES, PPS, PVC, PTFE, and other suitable materials.

[0259] In a second construction of a mass transfer tube **4202** and **4402**, a structural, porous tube **4020** is again used as a substrate, onto which a solid electrolyte membrane is applied. The porous substrate **4020** can include a sintered material such as PTFE, PVDF, PP or other suitable material, with porosity including, but not limited to the range of 10 microns to 500 microns. The electrolyte membrane, which selectively transports water and not gases, is applied onto the outer surface of the substrate tube **4020** through spraying, dipping or other deposition methods. In some embodiments, the thickness range of the electrolyte membrane is in a range that includes, but is not limited to 10 microns to 100 microns. A wall thickness range of the structural porous substrate tube **4020** includes, but is not limited to 0.005" to 0.050". In some embodiments, the porous substrate tube **4020** is formed of hydrophilic materials, in order to promote transfer of water through the sintered material and to the surface of the microporous membrane.

[0260] In a third construction of a mass transfer tube **4202** and **4402**, a structural porous or perforated tube **4020** is used as a mechanical support, onto which a hydrophobic woven plastic or a hydrophobic non-woven plastic including, but not limited to meltblown and spunbonded olefins, or a microporous membrane or solid electrolyte membrane is attached. A porous tube **4020** may be produced from sintered PVDF, PP or other suitable material with porosity in the range that includes, but is not limited to 10 microns to 500 microns. A perforated tube **4020** with porosity in the range that includes, but is not limited to 0.05" to 0.5" may be produced by injection or compression molding PP, HDPE, PVDF, or other suitable material. The structural tube **4020** may have circular cross section, or it may use a foil-shape or other combination of circular and angular sections that result in improved air flow directed perpendicular to its axis (FIG. **5**). Certain cross sections, such as the foil-shape, will enable assembly of the porous and perforated structures **4020** and membranes from sheet materials, bonded at the trailing edge using heat staking, chemical adhesives and other methods known to one versed in the art.

[0261] As shown in FIGS. **26-45**, in some embodiments, each heat transfer tube **4201** is longer than each mass transfer tube **4202**. In some embodiments, each heat transfer tube **4401** is longer than each mass transfer tube **4402**. In some embodiments, each mass transfer tube **4402** is longer than each heat transfer tube **4501**. In some embodiments, the heat transfer tubes **4201**, **4301**, **4401** and **4501** and mass transfer tubes **4202** and **4402** are of approximately equal length, and may utilize the coupling devices **4050** and **4053** shown in FIGS. **35** and **38** for connection to the manifold reservoirs **4221**, **4222** and **4421**.

[0262] In some embodiments, each mass transfer tube **4202** is longer than each heat transfer tube **4201**, and the mass transfer tubes **4202** are located concentrically within larger diameter heat transfer tubes **4201**. Such embodiments are identical to those shown in FIGS. **27** and **28**, with the exception that supply air **4005** is fed to the mass transfer tubes **4202** and liquid desiccant is fed to the heat transfer tube **4201**.

[0263] In some embodiments, the mass transfer tubes **4202** and **4402** may be partially or entirely formed from a water vapor permeable material. In some embodiments, the mass transfer tubes **4202** and **4402** can include a porous support material (e.g., a scaffolding) and a water vapor permeable material. Examples of mass transfer tube materials are those selected from the group consisting of a woven plastic, non-woven plastic such as a spunbonded olefin, microporous plastic, structural porous tube covered with a microporous plastic, a structural porous tube covered with a water-permeable, microporous polymer electrolyte membrane, or a combination thereof. Examples of solid or monolithic, water permeable materials include sulfonated tetrafluoroethylene based fluoropolymer-copolymer (e.g., Nafion™, sold by DuPont), water conducting fluoropolymers, and non-fluorinated proton conducting polymers (e.g., NanoClear™, sold by Dais Analytic). Such water permeable, microporous membranes are generally formed from hydrophilic materials. As used herein "hydrophilic" refers to materials with a contact angle of greater than 90° (e.g., at least 100°, at least 115°, at least 120°, or at least 135°). As used herein, "covered" includes, but is not limited to, instances where a material is coated onto a substrate and instances where a material (such as a film) is wrapped over or shrink wrapped onto the substrate. An example of a porous support material formed into a foil shape **4020** is shown in FIG. **5**.

[0264] In some embodiments, the heat transfer tubes **4201**, **4301**, **4401** and **4501**, mass transfer tubes **4202** and **4402**, coupling devices **4050**, **4051** and **4053**, manifold reservoirs **4221**, **4222** and **4421**, and other associated parts of the duct systems can include a material selected from the group consisting of polyvinylidene difluoride (PVDF), polypropylene (PP), high-density polyethylene (HDPE), polytetrafluoroethylene (PTFE), polyvinyl chloride (PVC), polyphenylene sulfide (PPS), polyethersulfone (PES), metal, and combinations thereof. In some embodiments, the wall can be formed of a metal coated by polyvinylidene difluoride (PVDF), polypropylene (PP), high-density polyethylene (HDPE), polytetrafluoroethylene (PTFE), or combinations thereof. In other embodiments, the wall can be formed of polyvinylidene difluoride (PVDF), polypropylene (PP), high-density polyethylene (HDPE), polytetrafluoroethylene (PTFE), polyvinyl chloride (PVC), polyphenylene sulfide (PPS), polyethersulfone (PES), or combinations thereof. Examples of metal that can be useful include, but are not limited to, titanium, stainless steel, and other corrosion resistant metals or alloys.

[0265] The foregoing is provided for purposes of illustrating, explaining, and describing embodiments of this invention. Modifications and adaptations to these embodiments will be apparent to those skilled in the art and may be made without departing from the scope or spirit of this invention.

1. A heat and mass exchanger system, comprising:

a plurality of exchange components extending across a heat and mass exchanger (HMX) duct, wherein a flow through said HMX duct is cross-flow relative to said exchange components, wherein said exchange components comprise a plurality of first elongated, hollow conduits and a plurality of second elongated, hollow conduit,

wherein either said first elongated, hollow conduits or said second elongated, hollow conduits have water vapor permeable exterior walls, and

wherein heat and mass exchanger system is adapted for a carrier air stream and a liquid desiccant stream to flow in contact with opposite sides of said water vapor permeable exterior walls.

2. The system according to claim **1**, wherein said system is adapted to transport a liquid desiccant stream through a body selected from said HMX duct, said first elongated, hollow conduits, and said second elongated, hollow conduits; and

wherein said system is adapted to transport a carrier air stream through a different body selected from said HMX duct, said first elongated, hollow conduits, and said second elongated, hollow conduits.

3. The system according to claim 1, wherein said first elongated, hollow conduits are each spaced apart from the others, and wherein said second elongated, hollow conduits are each spaced apart from the others.

4. The system according to claim 1, wherein said exchange components comprise tube-in-tube exchange components, wherein each tube-in-tube components comprises one first elongated, hollow conduit within one second elongated, hollow conduit, forming an inner flow channel within said first elongated, hollow conduit and an outer flow channel external to said first elongated, hollow conduit and adjacent a wall of said second elongated, hollow conduit.

5. The system according to claim 4, wherein said pluralities of first and second elongated, hollow conduits extend laterally across the HMX duct, and said system further comprising a plurality of third elongated, hollow conduits extending across said HMX duct.

6. The system according to claim 5, wherein said third elongated, hollow conduits extend laterally across the HMX duct.

7. The system according to claim 5, wherein said third elongated, hollow conduits extend transverse to said first and second elongated, hollow conduits.

8. The system according to claim 5, wherein each of said tube-in-tube exchanger components further comprises one of the plurality of third elongated, hollow conduits within said first elongated, hollow conduit, where each of said third elongated, hollow conduits define a central lumen within said third elongated, hollow conduit, wherein the inner flow channel is defined by an exterior of the third elongated, hollow conduit and an interior of the first elongated, hollow conduit.

9. The system according to claim 4, adapted such that a coolant stream flows through said inner channel, a liquid desiccant stream flows through said outer channel, and a carrier air stream flows through said HMX duct.

10. The system according to claim 9, wherein the system is configured to flow the coolant stream and the liquid desiccant stream in a counter-flow arrangement.

11. The system according to claim 4, adapted such that a carrier air stream flows through said inner channel, liquid desiccant stream flows through said outer channel, and a coolant stream flows through said HMX duct.

12. The system according to claim 11, wherein the system is configured to be carrier air stream and the liquid desiccant stream in a counter-flow arrangement.

13. The system according to claim 4, adapted such that a liquid desiccant stream flows through said inner channel, a carrier air stream flows through said outer channel, and said coolant stream flows through said HMX duct.

14. The system according to claim 13, wherein the system is configured to flow the liquid desiccant stream and the carrier air stream in a counter-flow arrangement.

15. The system according to claim 4, wherein each first elongated, hollow conduit is longer than each second elongated, hollow conduit.

16. The system according to claim 4, wherein each tube-in-tube exchanger component comprises a first end cap and a second end cap, wherein the first end cap sealably engages first ends of the first and second elongated, hollow conduit, and the second end cap sealably engages second ends of the first and second elongated, hollow conduit,

wherein said first end cap comprises at least one first end cap inner opening extending to said inner flow channel and at least one first end cap outer opening extending to said outer flow channel, and

wherein said second end cap comprises at least one second end cap inner opening extending to said inner flow channel and at least one second end cap outer opening extending to said outer flow channel.

17. The system according to claim 16, further comprising:

first and second inner manifold plates on opposite sides of said HMX duct; and

first and second outer manifold plates on opposite sides of said HMX duct, wherein said first and second inner manifold plates are between said first and second outer manifold plates,

wherein said first inner manifold plate and said first outer manifold plate engage said first end cap of each tube-in-tube exchanger component, and

wherein said second inner manifold plate and said second outer manifold plate engage said second first end cap of each tube-in-tube exchanger component.

18. The system according to claim 15, further comprising:

first and second inner manifold plates on opposite sides of said HMX duct; and

first and second outer manifold plates on opposite sides of said HMX duct, wherein said first and second inner manifold plates are between said first and second outer manifold plates,

wherein said first and second inner manifold plates engage first and second ends of each of said second elongated, hollow conduits, and

wherein said first and second outer manifold plates engage first and second ends of each of said first elongated, hollow conduits.

19. The system according to claim 1, further comprising a plurality of disrupters extending from at least one wall of said HMX duct.

20. The system according to claim 19, wherein the flow disrupters extend across said HMX duct.

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