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(54) **SYSTEMS AND METHODS FOR REMOVING CARBON DIOXIDE FROM A FLUID**

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Related U.S. Application Data

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(60) Provisional application No. 63/480,463, filed on Jan. 18, 2023, provisional application No. 63/369,141, filed on Jul. 22, 2022.

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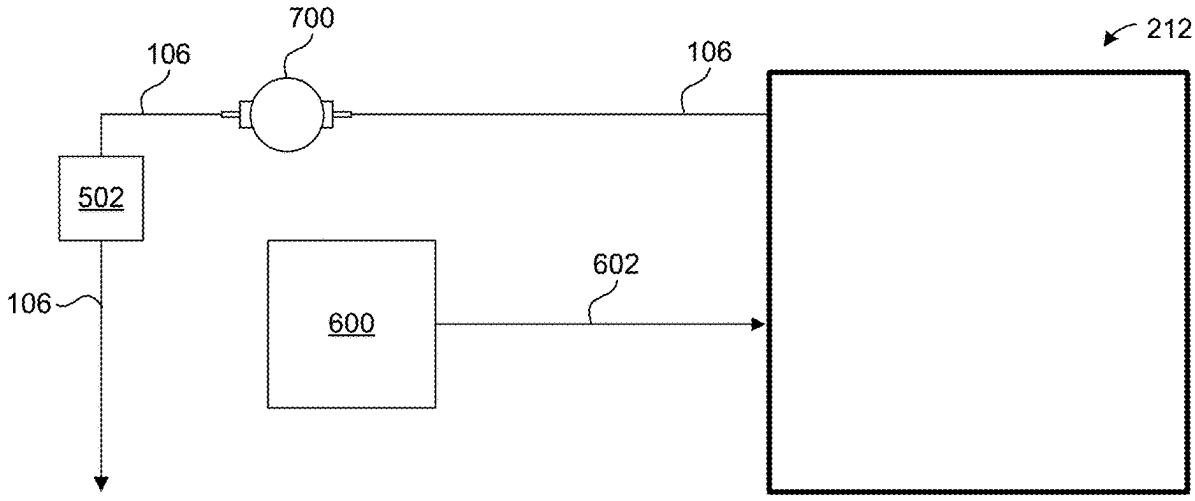
(52) **U.S. Cl.**
CPC ***B01D 53/0438*** (2013.01); *B01D 2257/504* (2013.01); *B01D 2259/40096* (2013.01)

(57) **ABSTRACT**

Some embodiments are directed to a system for extracting carbon dioxide from a fluid. The system can include a fluid source and a reactor. The reactor can include one or more chambers, and each chamber can include one or more monoliths for adsorbing carbon dioxide from the fluid. The chambers can be alternatively unsealed for a contacting mode and sealed for a regeneration mode. A power source can provide an electric current to the monoliths to release carbon dioxide adsorbed by the monoliths. Each chamber can include an array of monoliths. Each monolith can include a sorbent that adsorbs carbon dioxide from fluid. The system can include modular components such that the number of reactors can be increased or decreased.



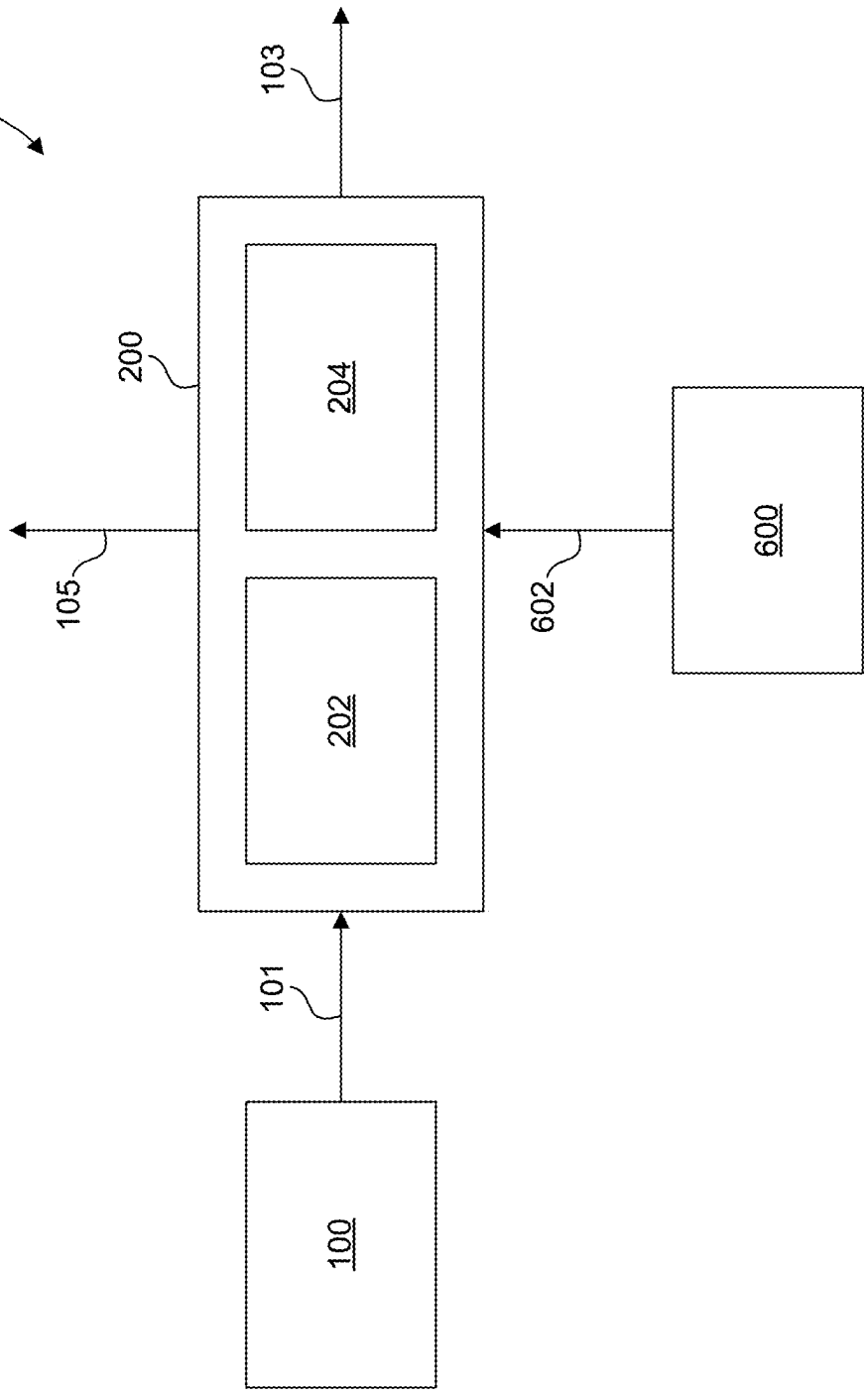


FIG. 1

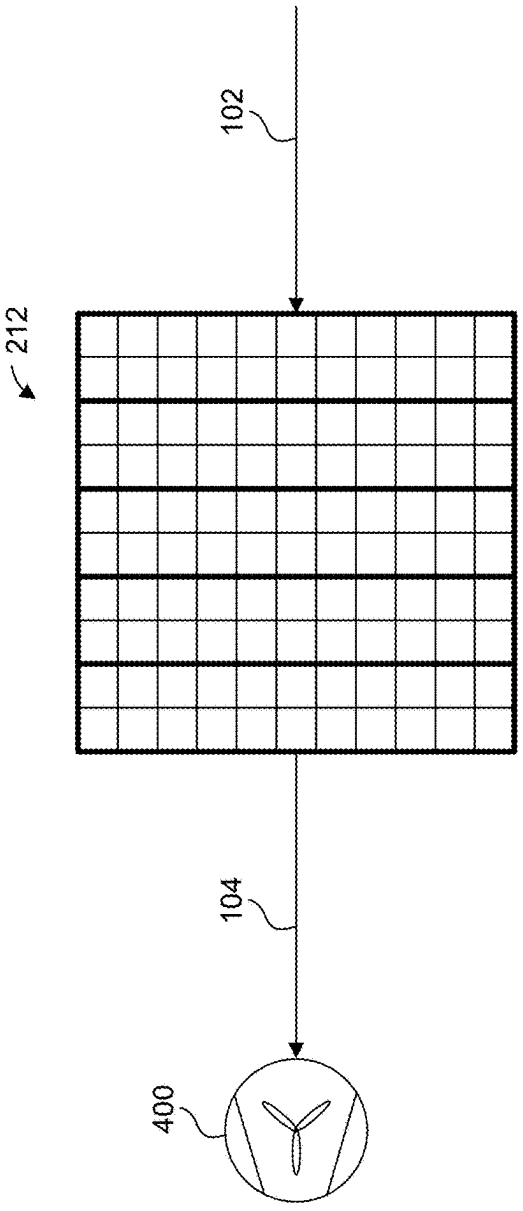


FIG. 2A

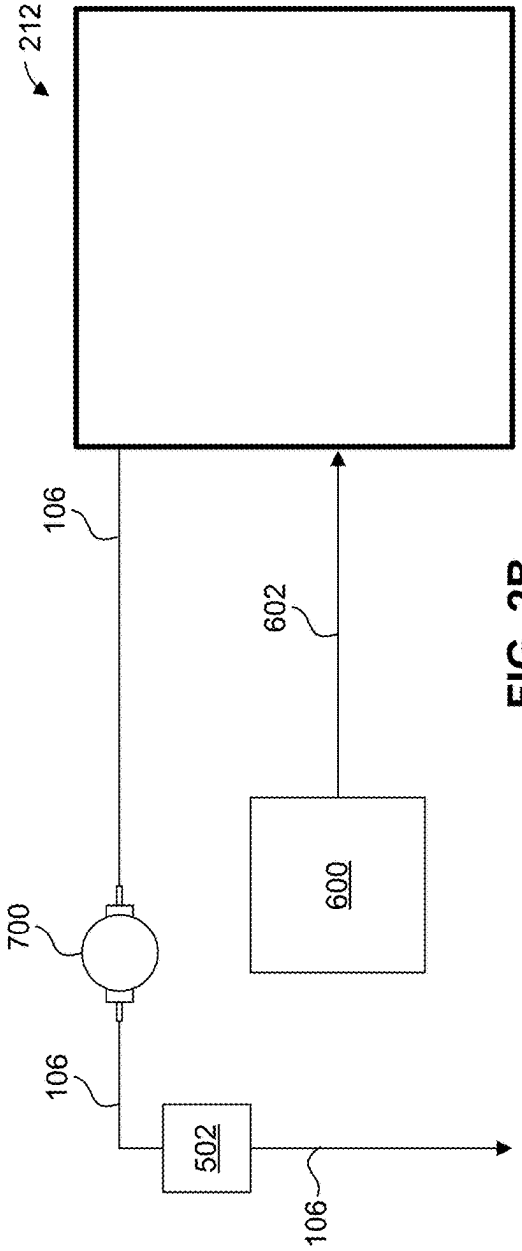


FIG. 2B

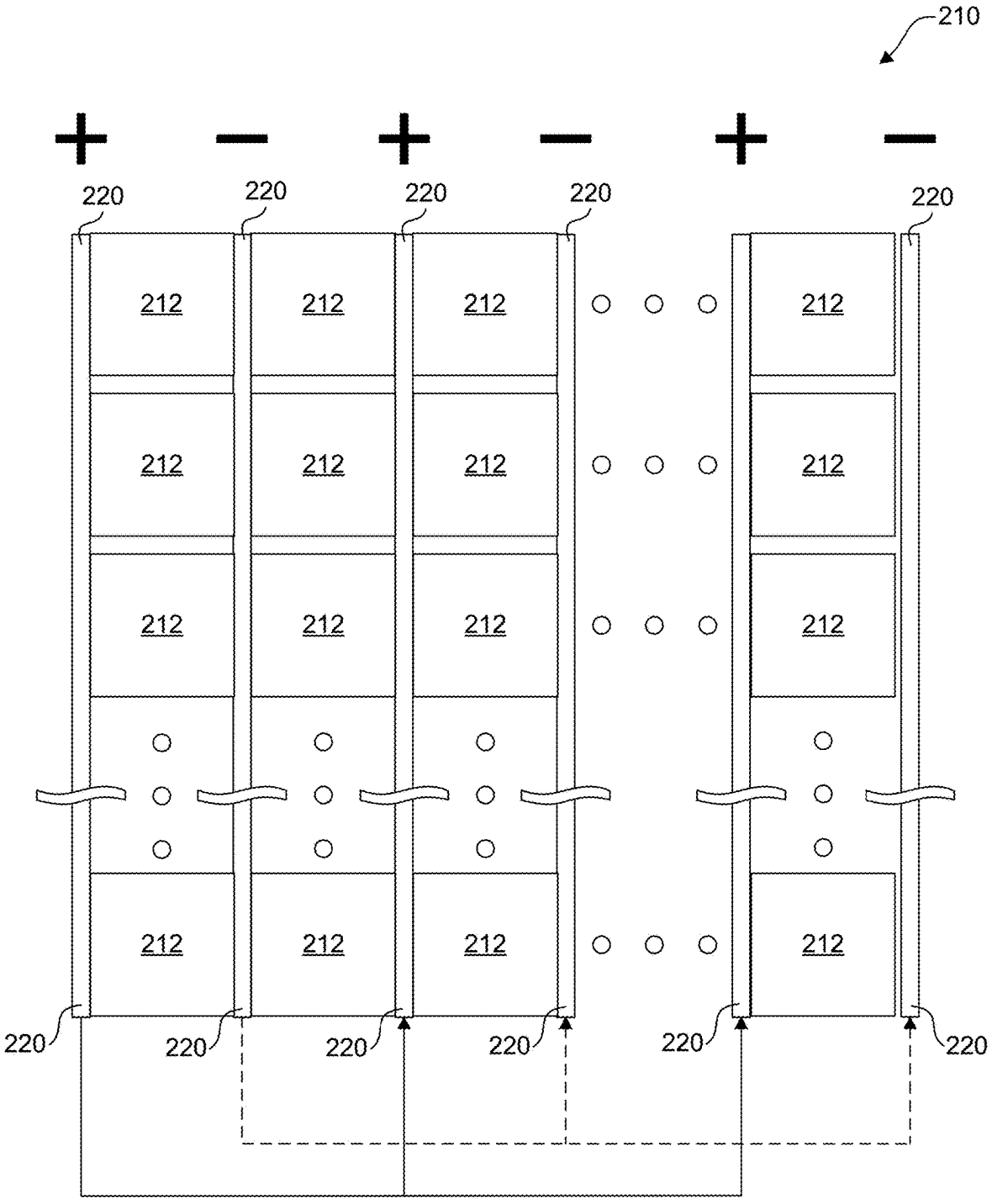

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FIG. 3

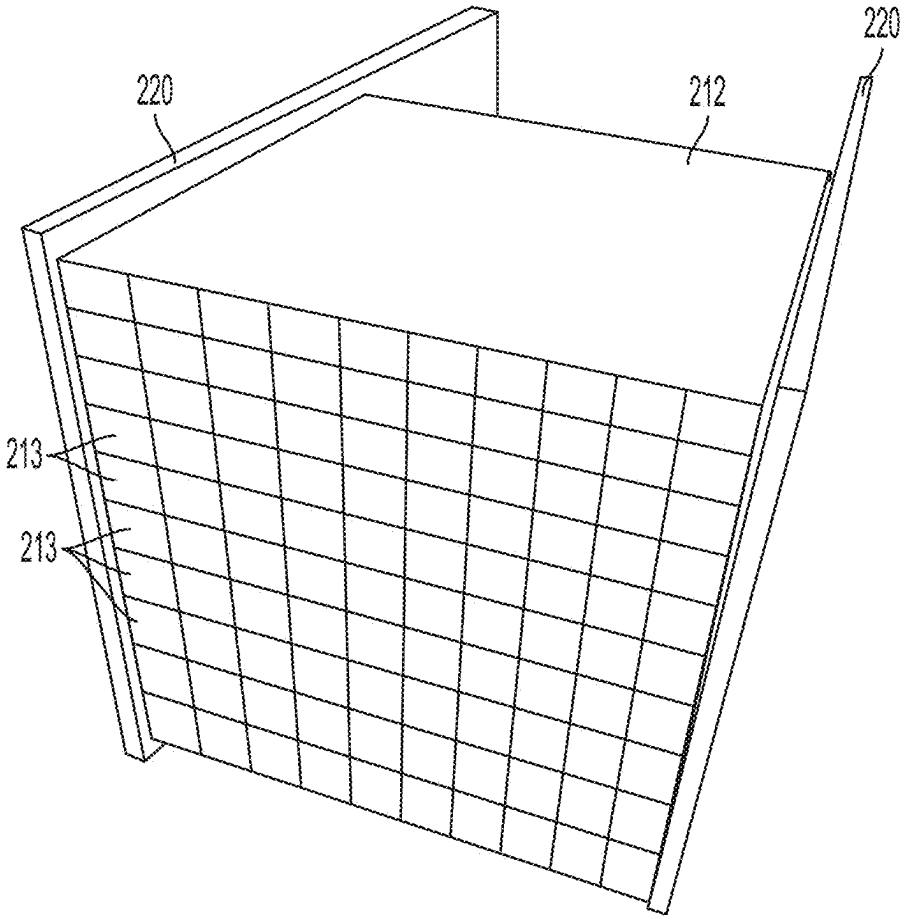

FIG. 4

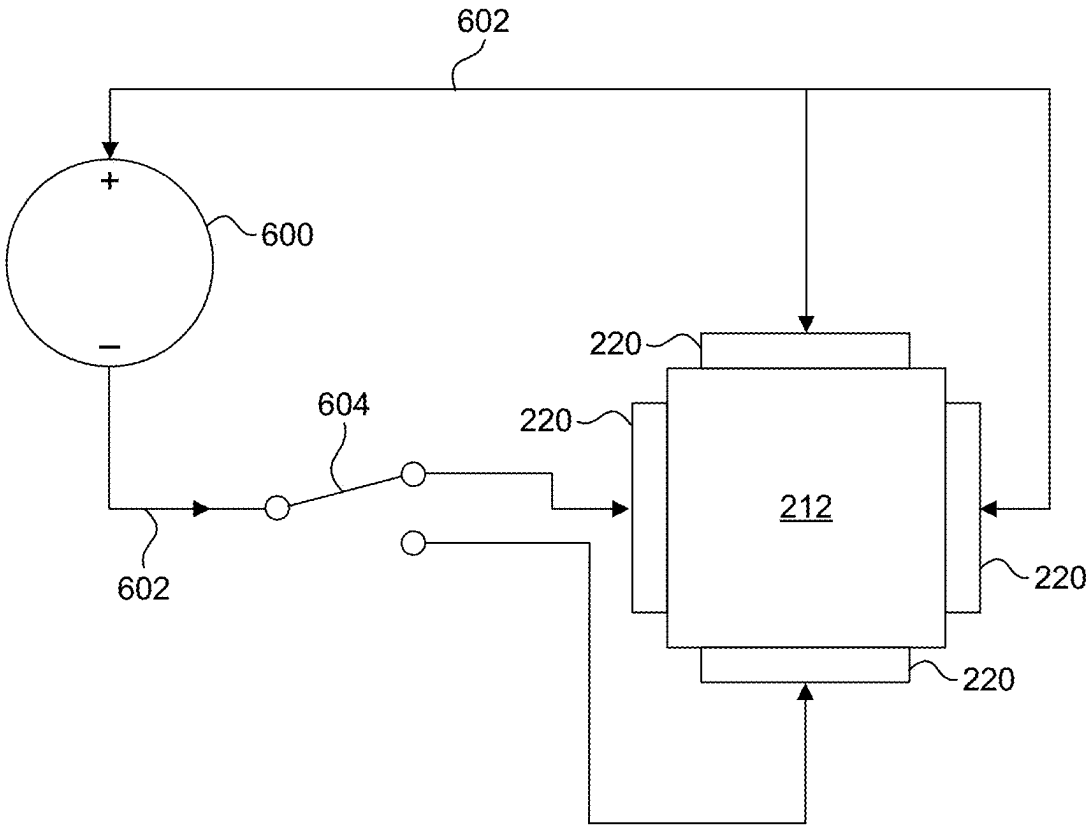

FIG. 5

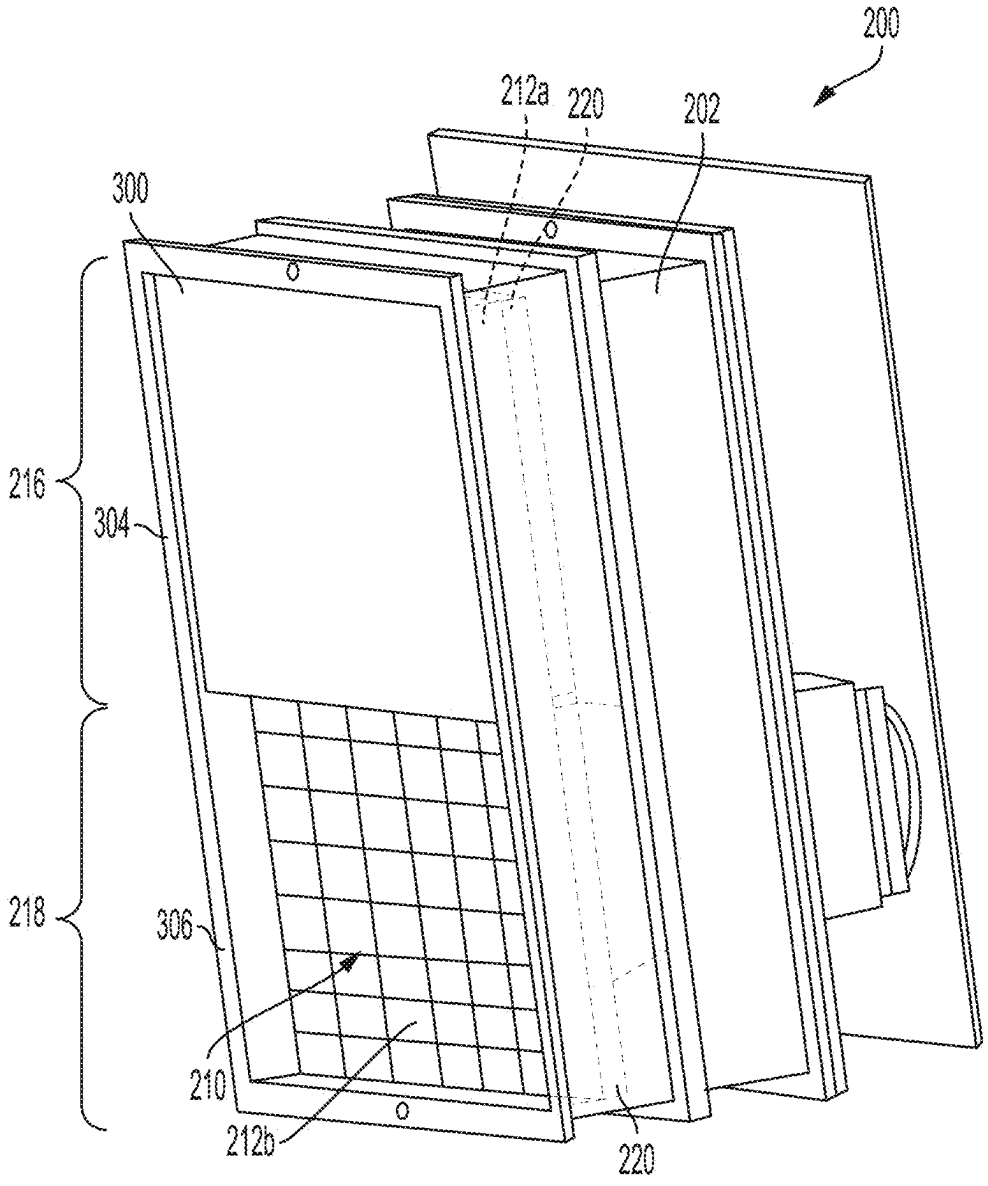

FIG. 6

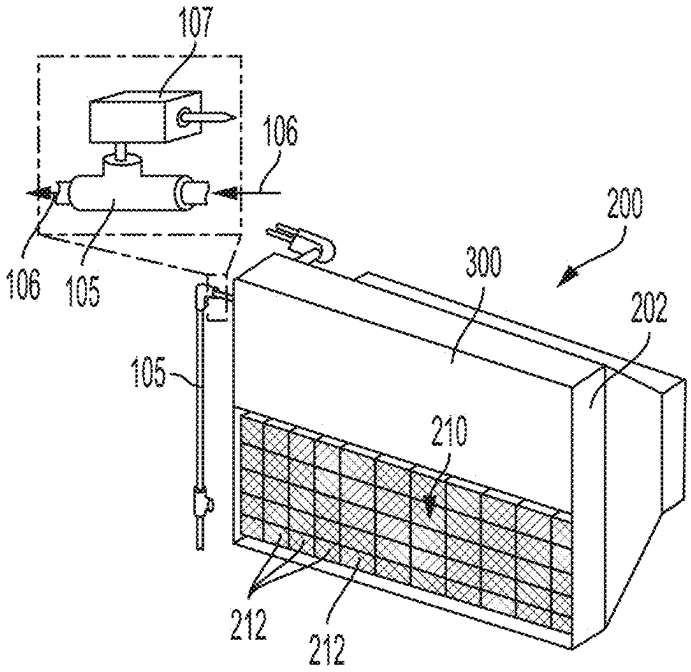

FIG. 7

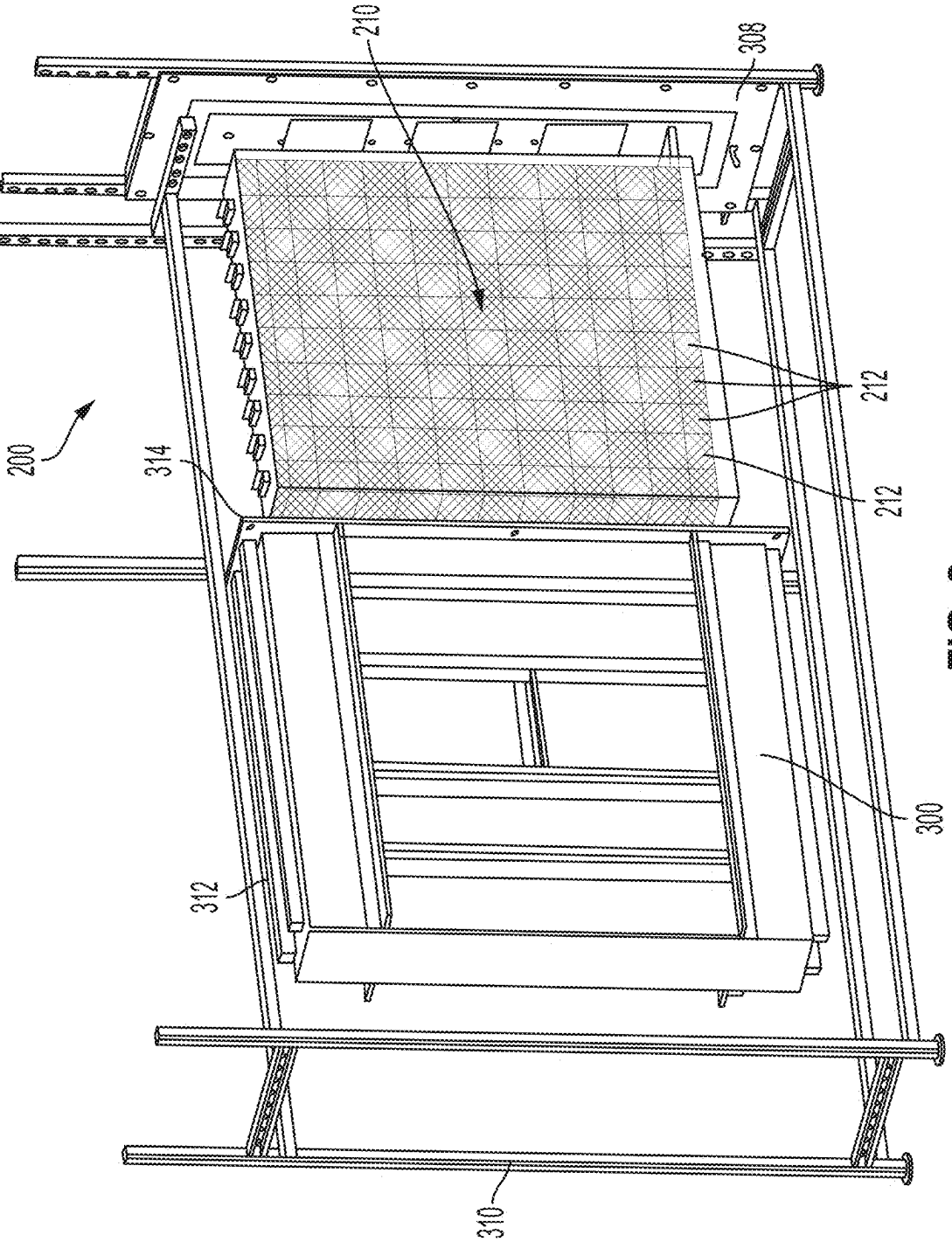

FIG. 8

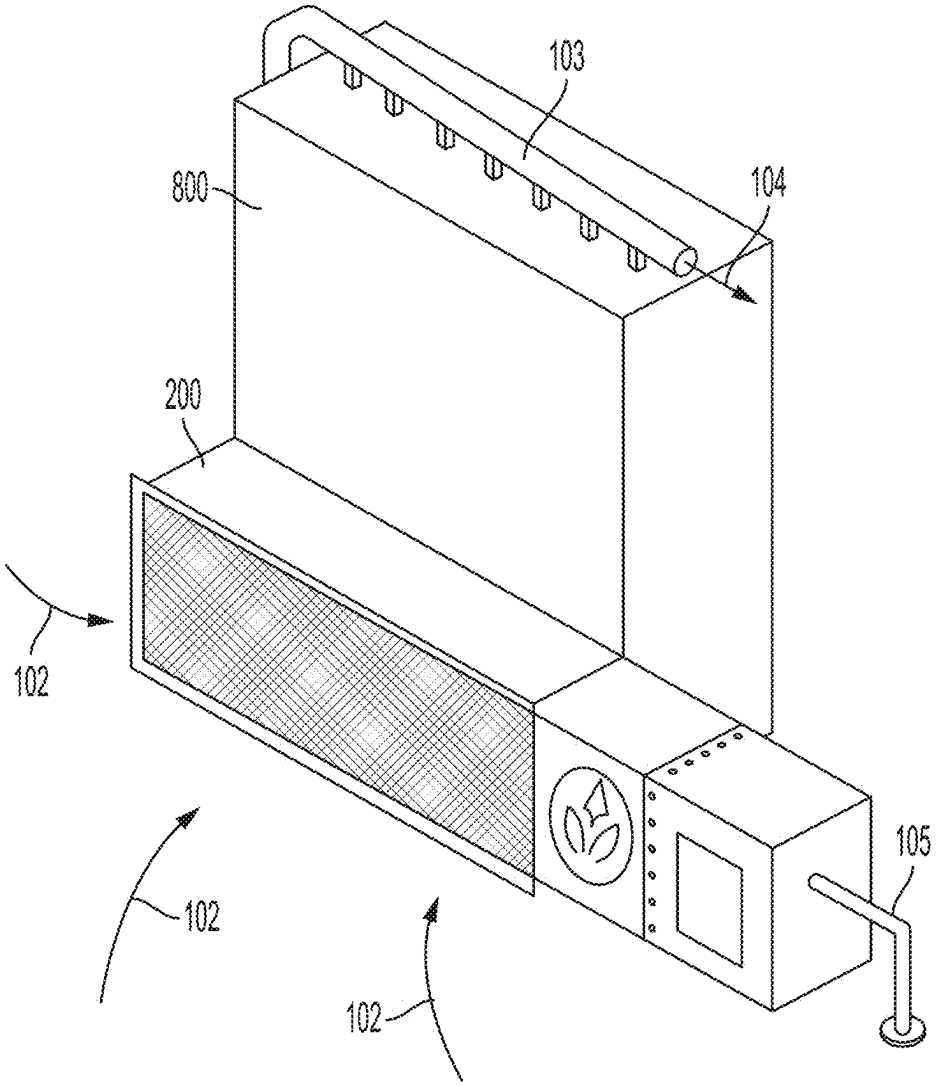

FIG. 9

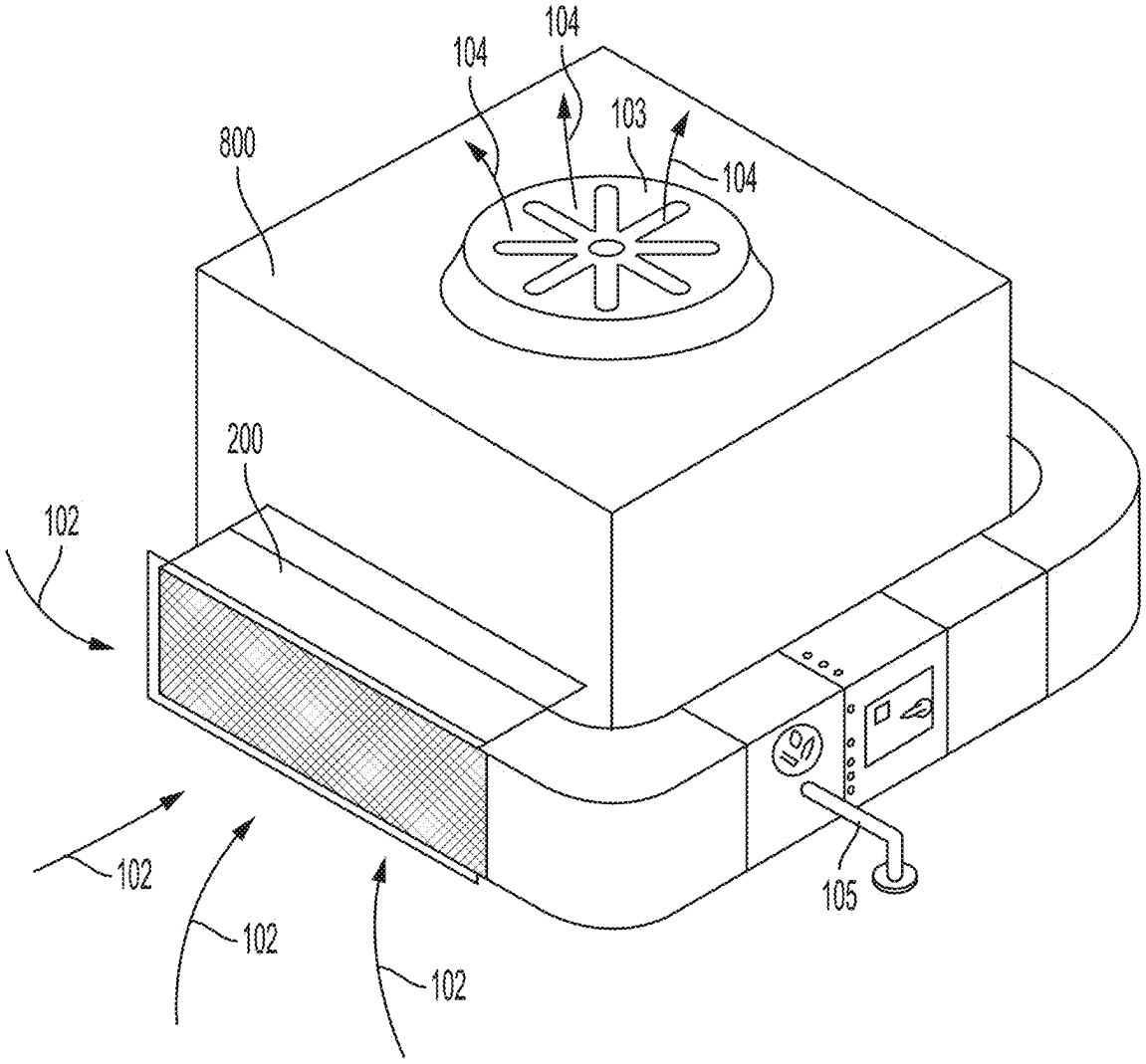

FIG. 10

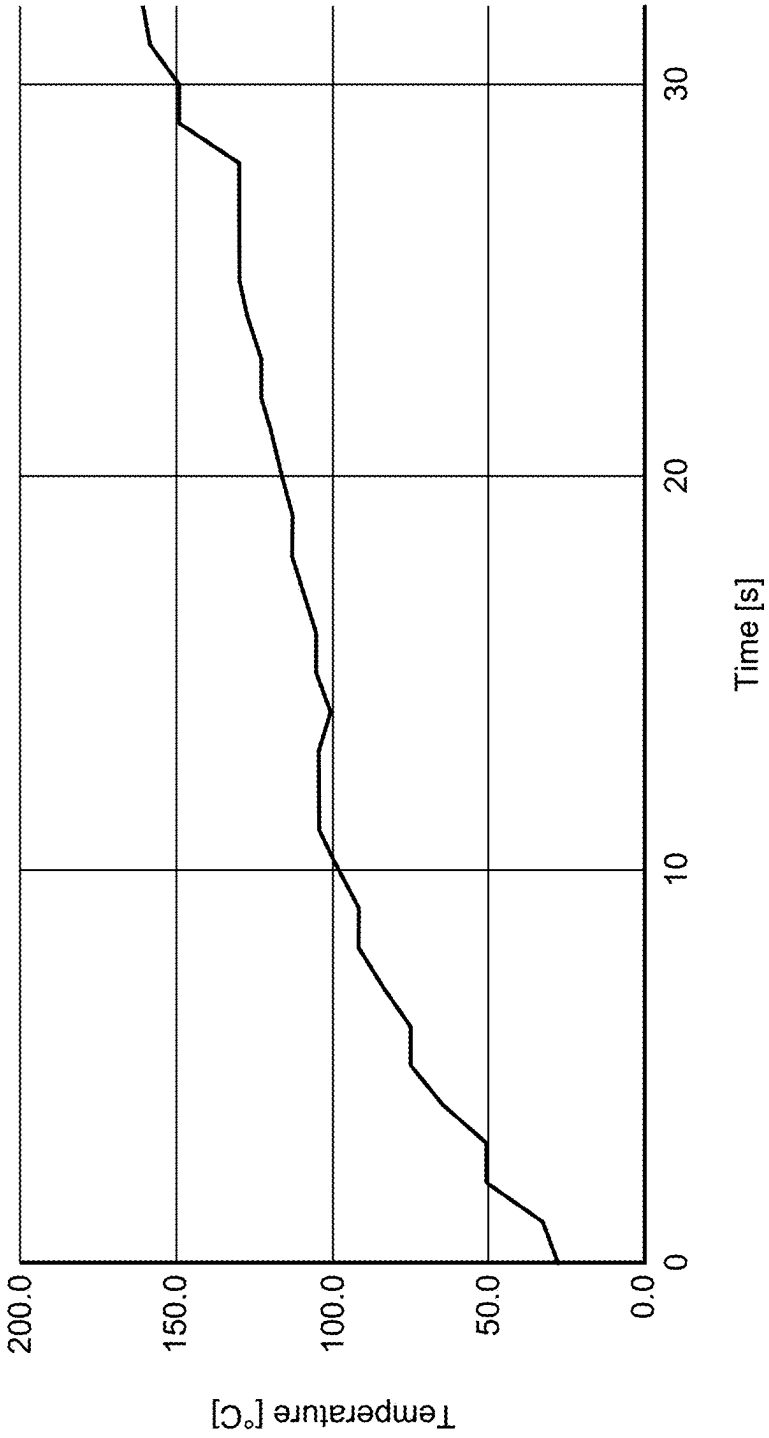

FIG. 11

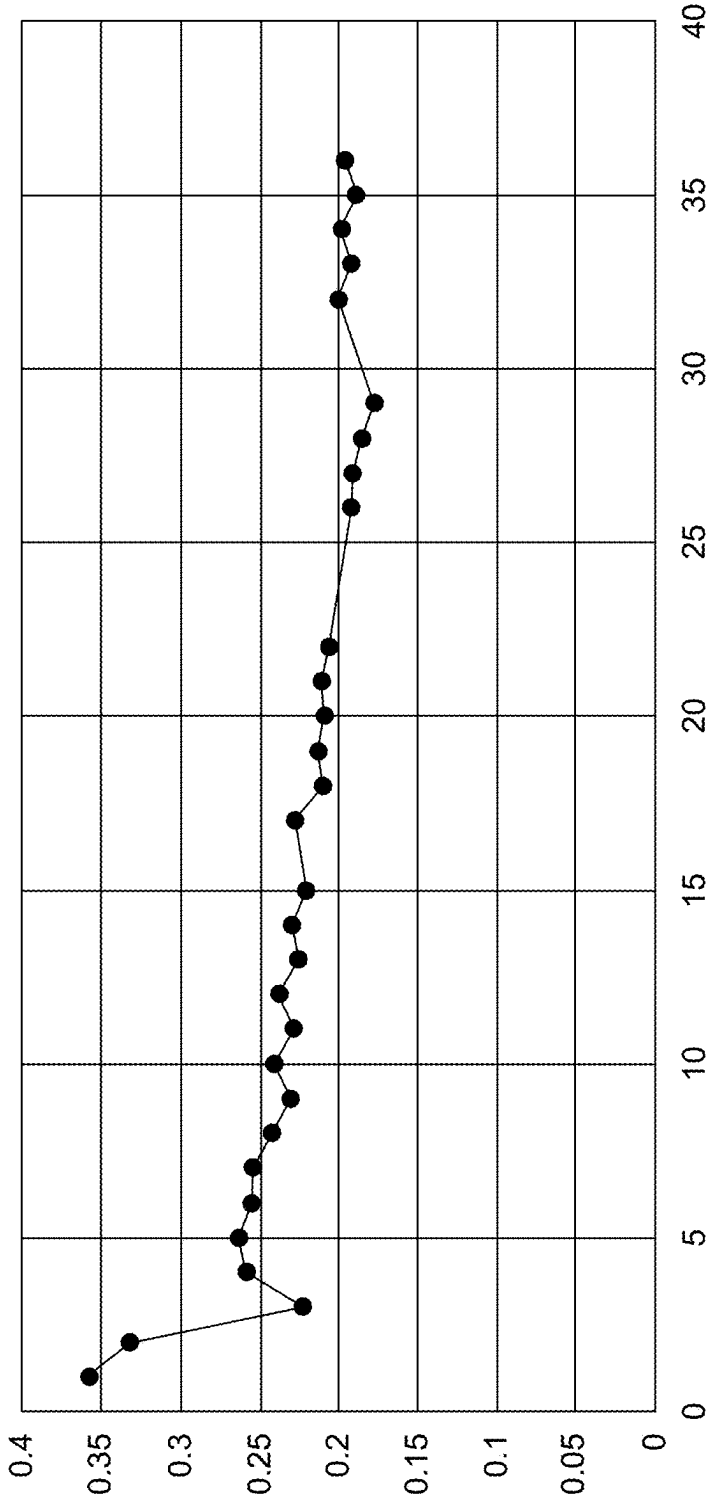

FIG. 12

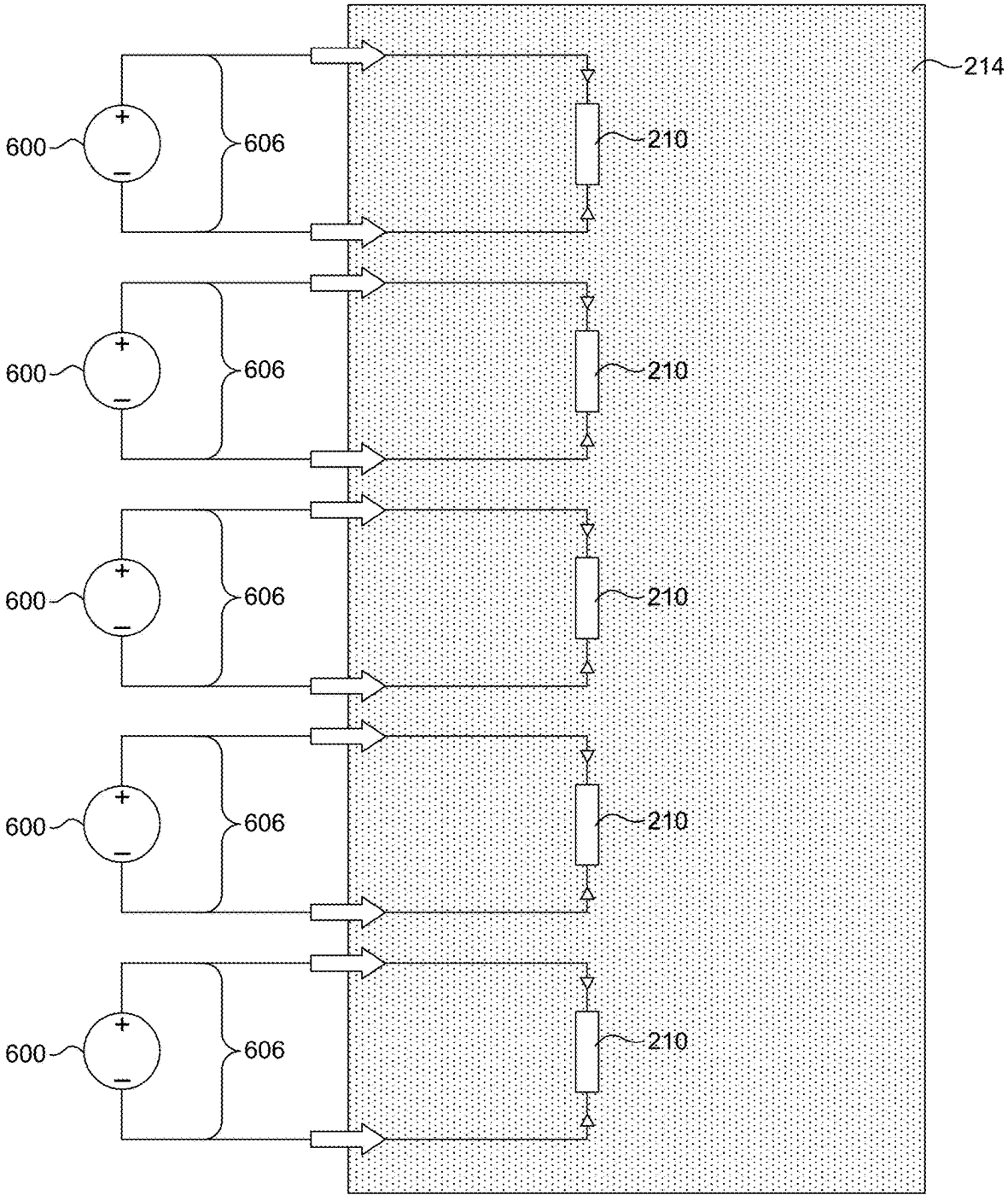

FIG. 13

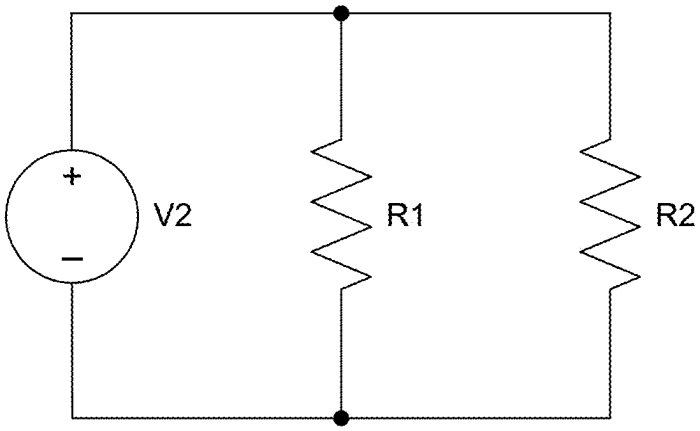

FIG. 14A

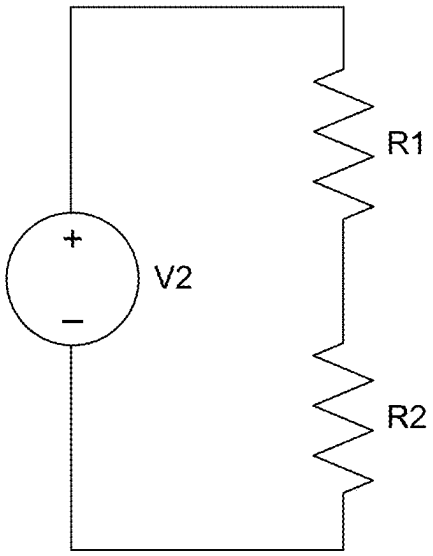

FIG. 14B

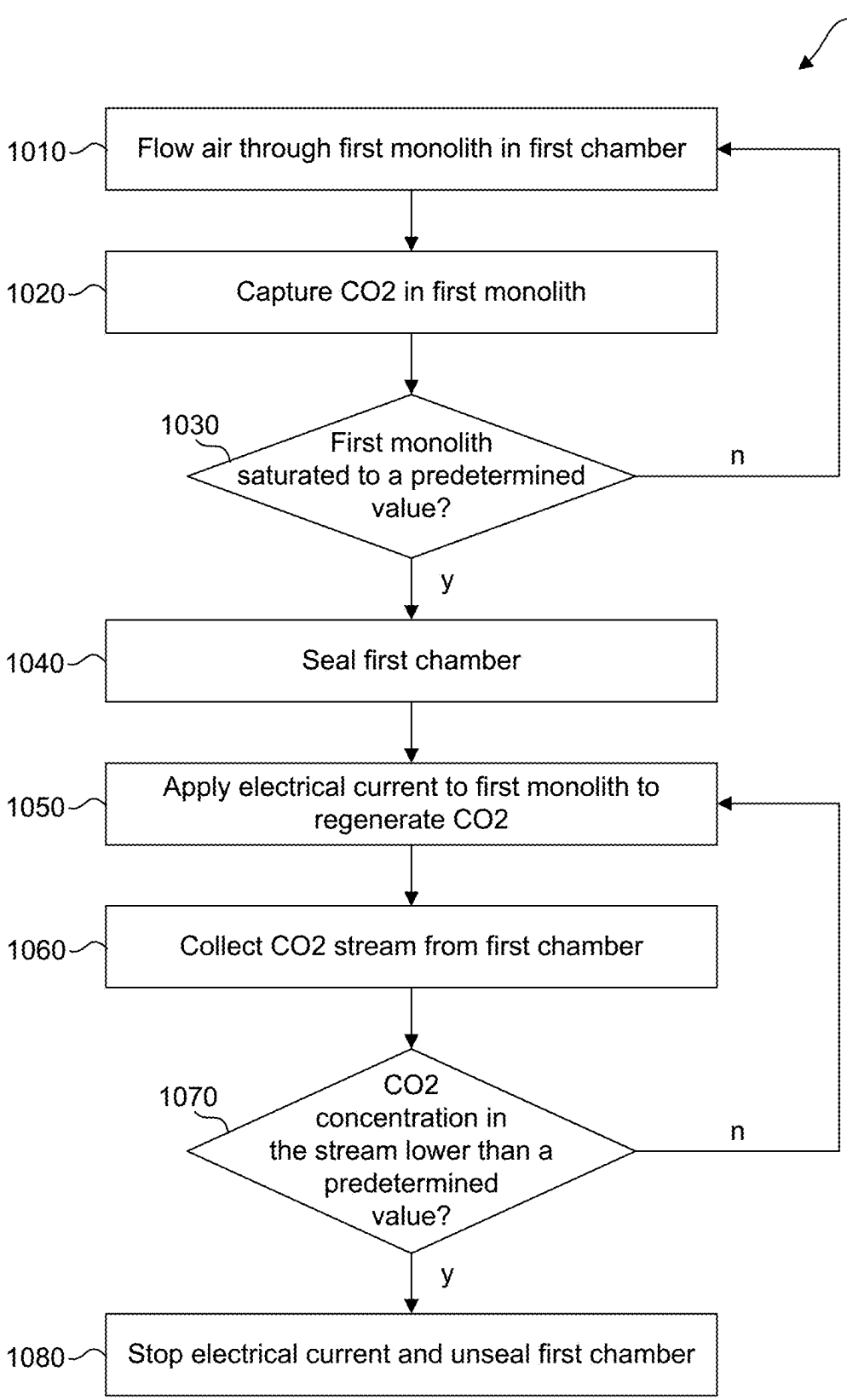
1000
1010
Flow air through first monolith in first chamber
1020
Capture CO2 in first monolith
1030
First monolith saturated to a predetermined value?
n
y
1040
Seal first chamber
1050
Apply electrical current to first monolith to regenerate CO2
1060
Collect CO2 stream from first chamber
1070
CO2 concentration in the stream lower than a predetermined value?
n
y
1080
Stop electrical current and unseal first chamber

FIG. 15

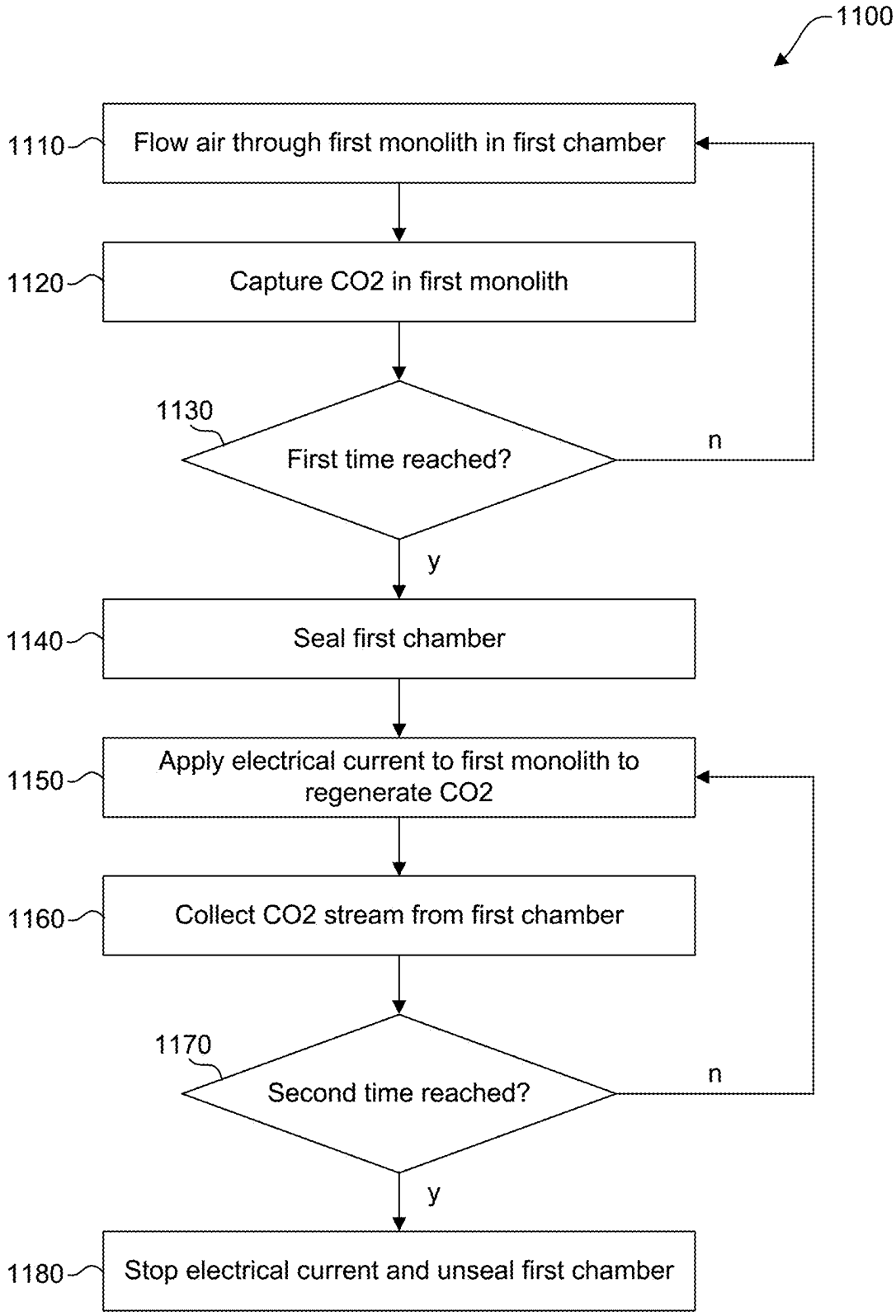
1100
1110
Flow air through first monolith in first chamber
1120
Capture CO2 in first monolith
1130
First time reached?
n
y
1140
Seal first chamber
1150
Apply electrical current to first monolith to regenerate CO2
1160
Collect CO2 stream from first chamber
1170
Second time reached?
n
y
1180
Stop electrical current and unseal first chamber

FIG. 16

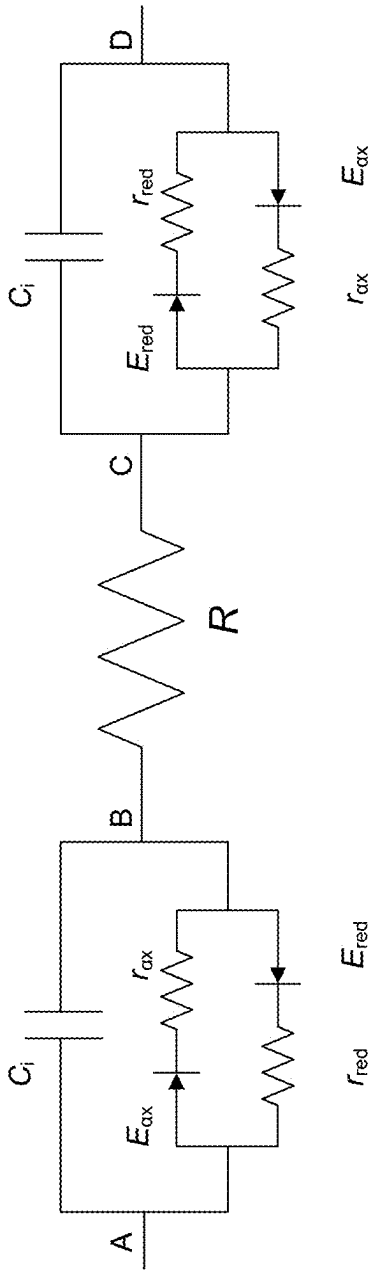
A
B
C
D
C_i
C_i
E_{ox}
r_{ox}
E_{red}
r_{red}
R
r_{red}
E_{red}
r_{ox}
E_{ox}
electrode | solution interface 1
Solution
electrode | solution interface 2

FIG. 17

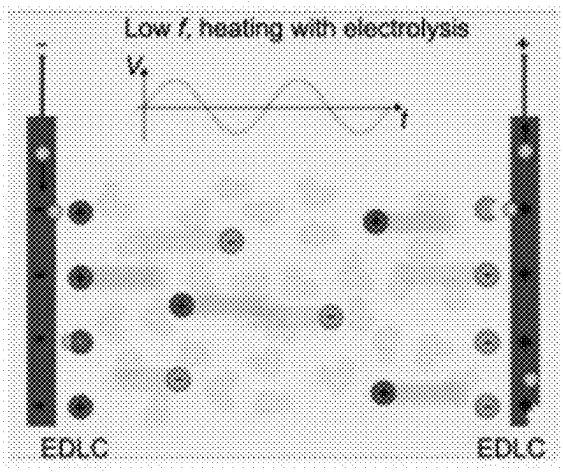

FIG. 18A

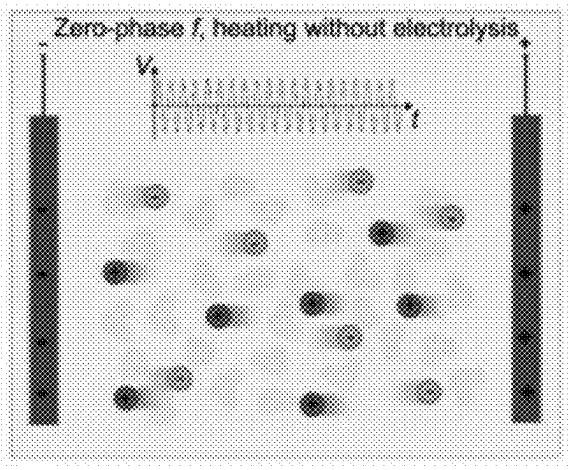

FIG. 18B

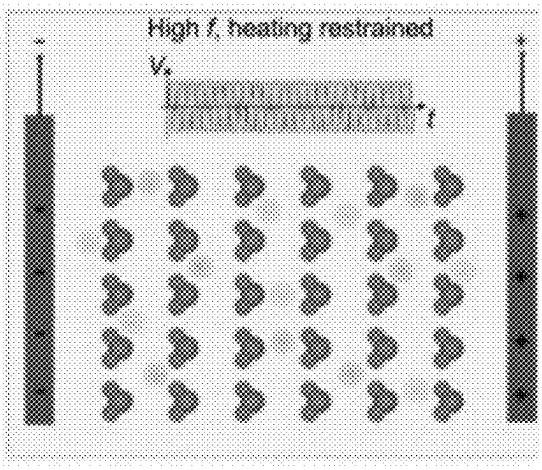

FIG. 18C

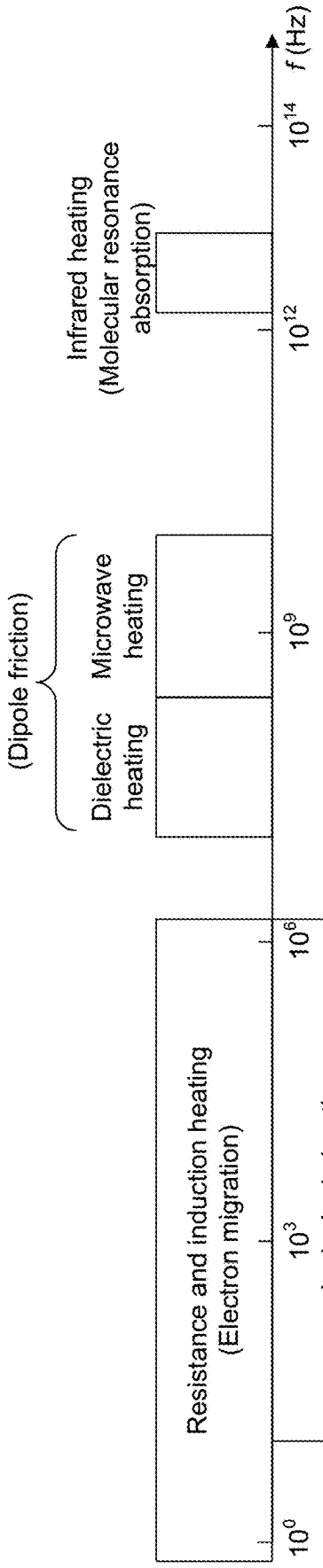
Resistance and induction heating
(Electron migration)
Ionic Joule heating
(Ions migration)
(Dipole friction)
Dielectric heating
Microwave heating
Infrared heating
(Molecular resonance absorption)
10^0
10^3
10^6
10^9
10^{12}
10^{14}
f (Hz)

FIG. 19

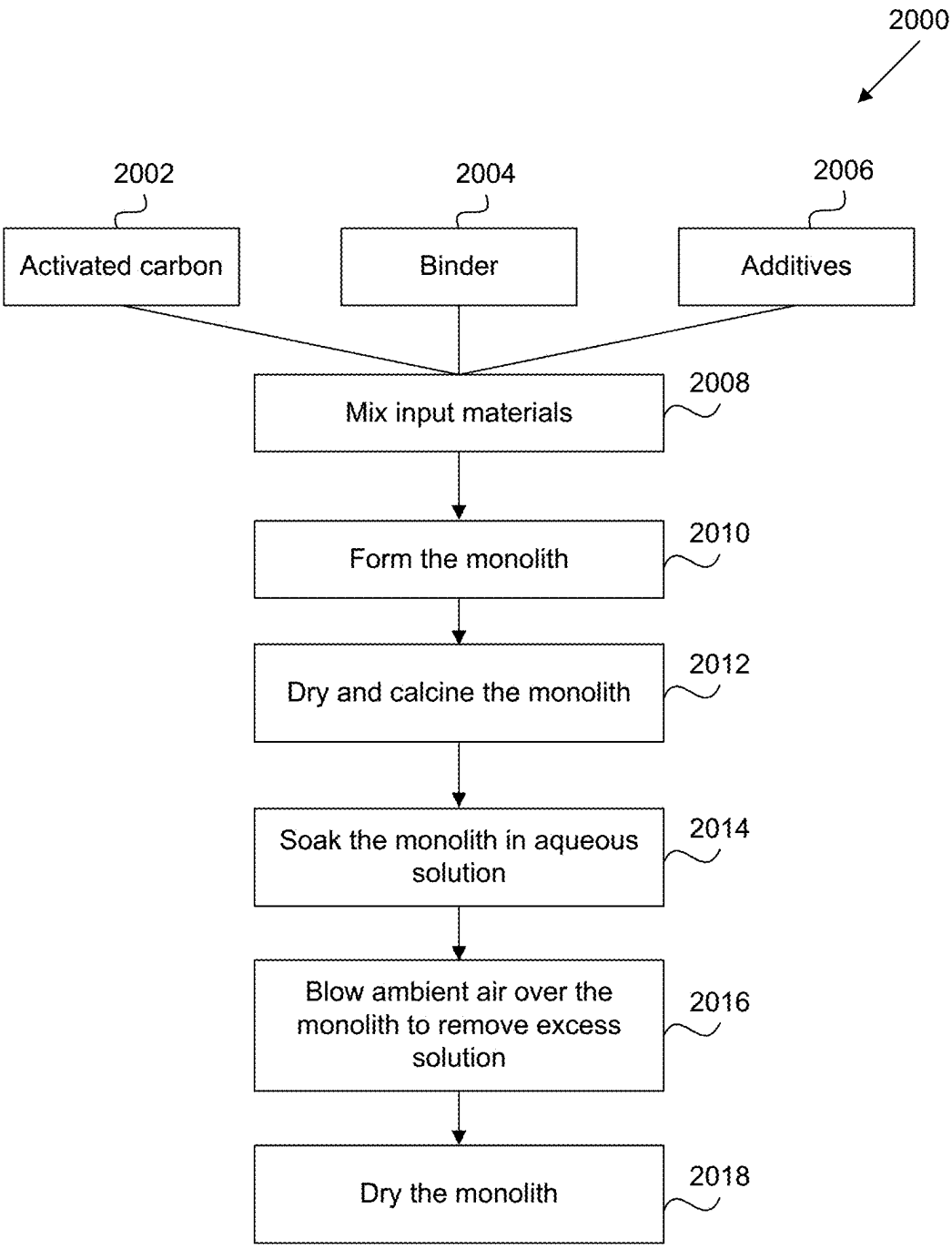
2000
2002
2004
2006
Activated carbon
Binder
Additives
Mix input materials
2008
Form the monolith
2010
Dry and calcine the monolith
2012
Soak the monolith in aqueous solution
2014
Blow ambient air over the monolith to remove excess solution
2016
Dry the monolith
2018

FIG. 20

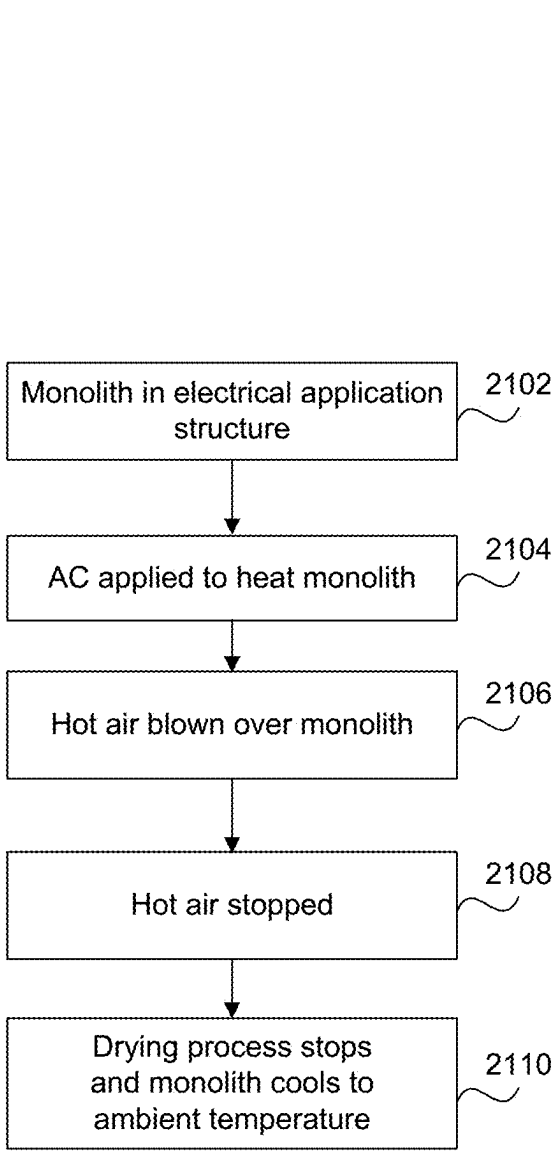
2100
Monolith in electrical application structure
2102
AC applied to heat monolith
2104
Hot air blown over monolith
2106
Hot air stopped
2108
Drying process stops and monolith cools to ambient temperature
2110

FIG. 21

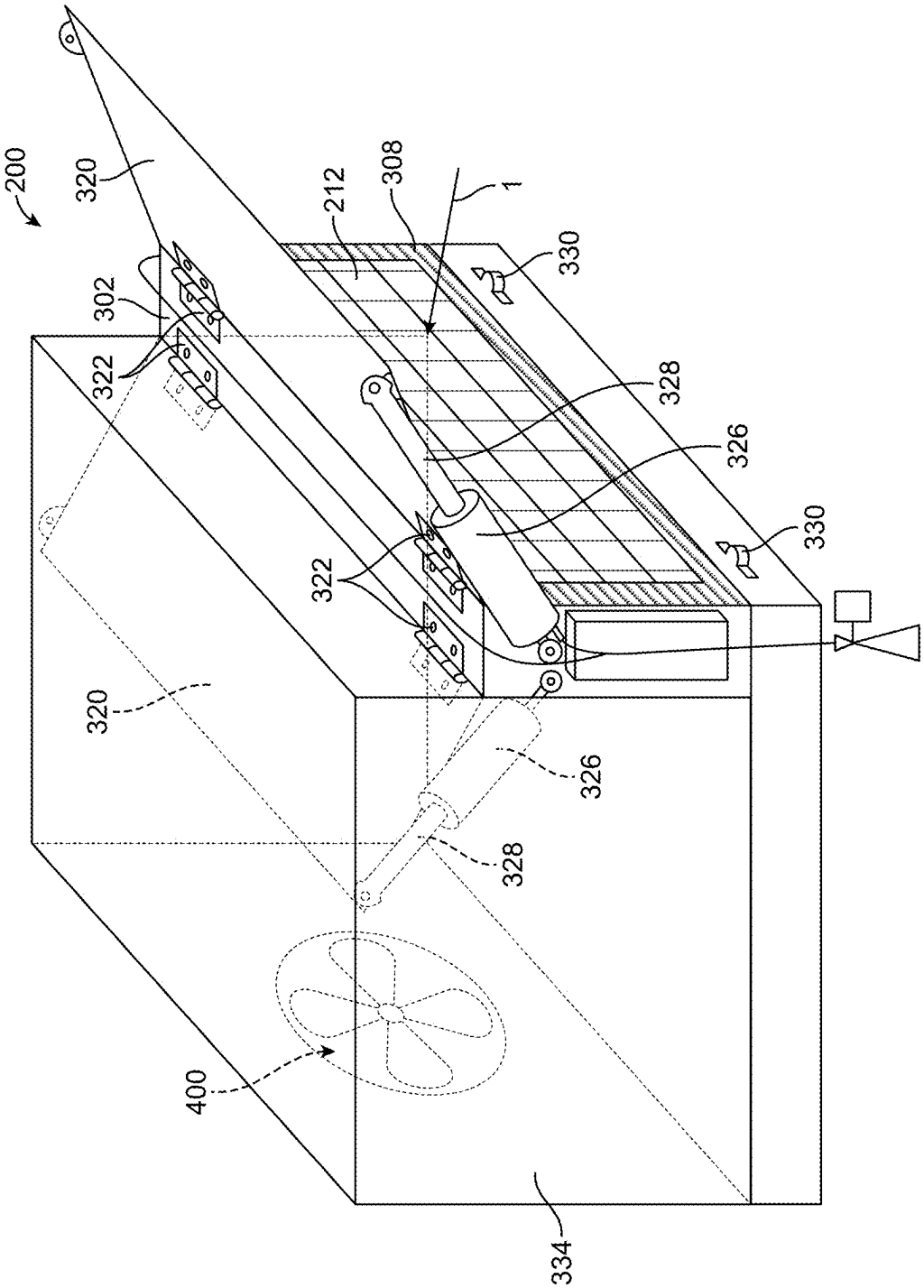

FIG. 22

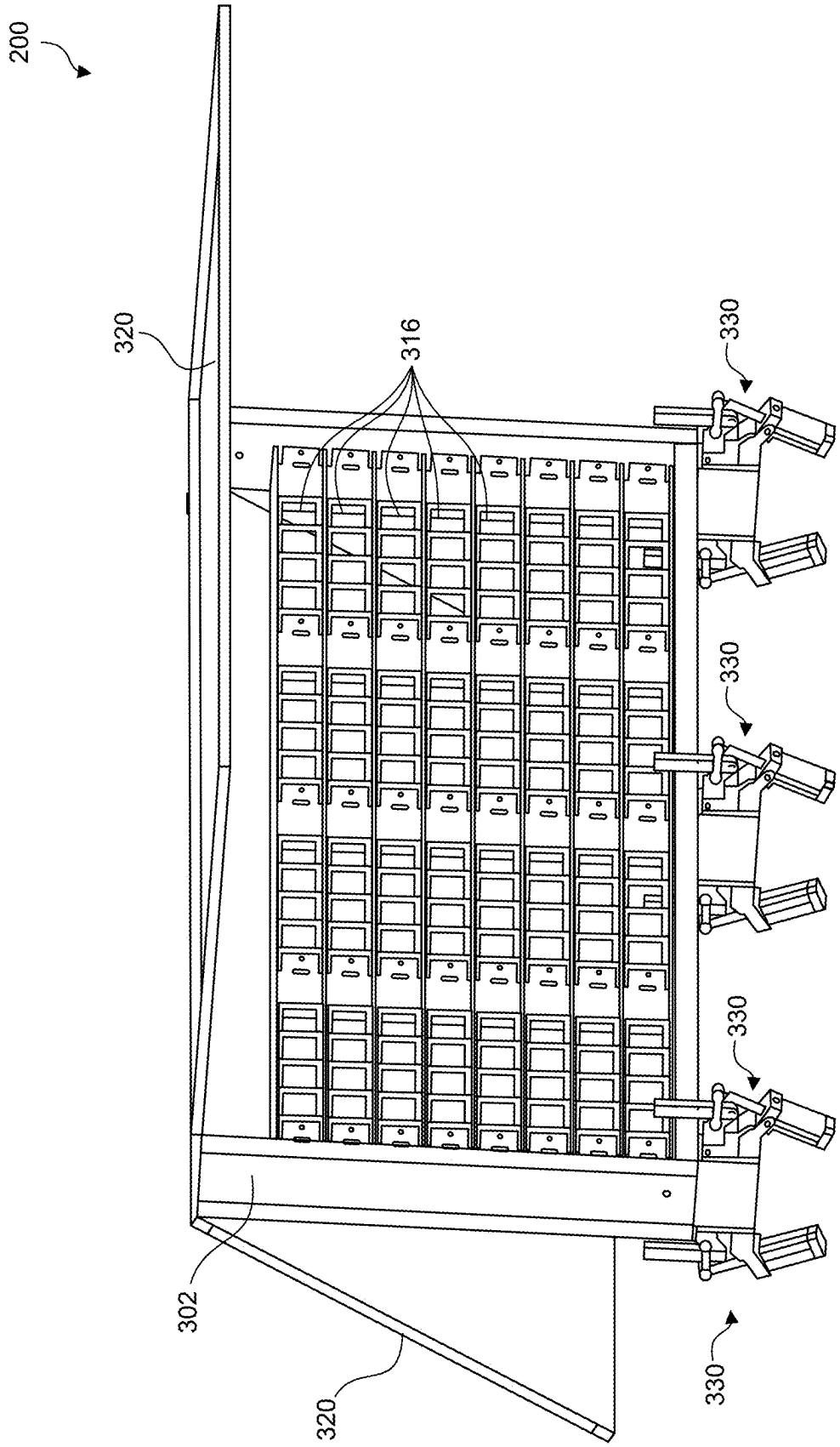

FIG. 23

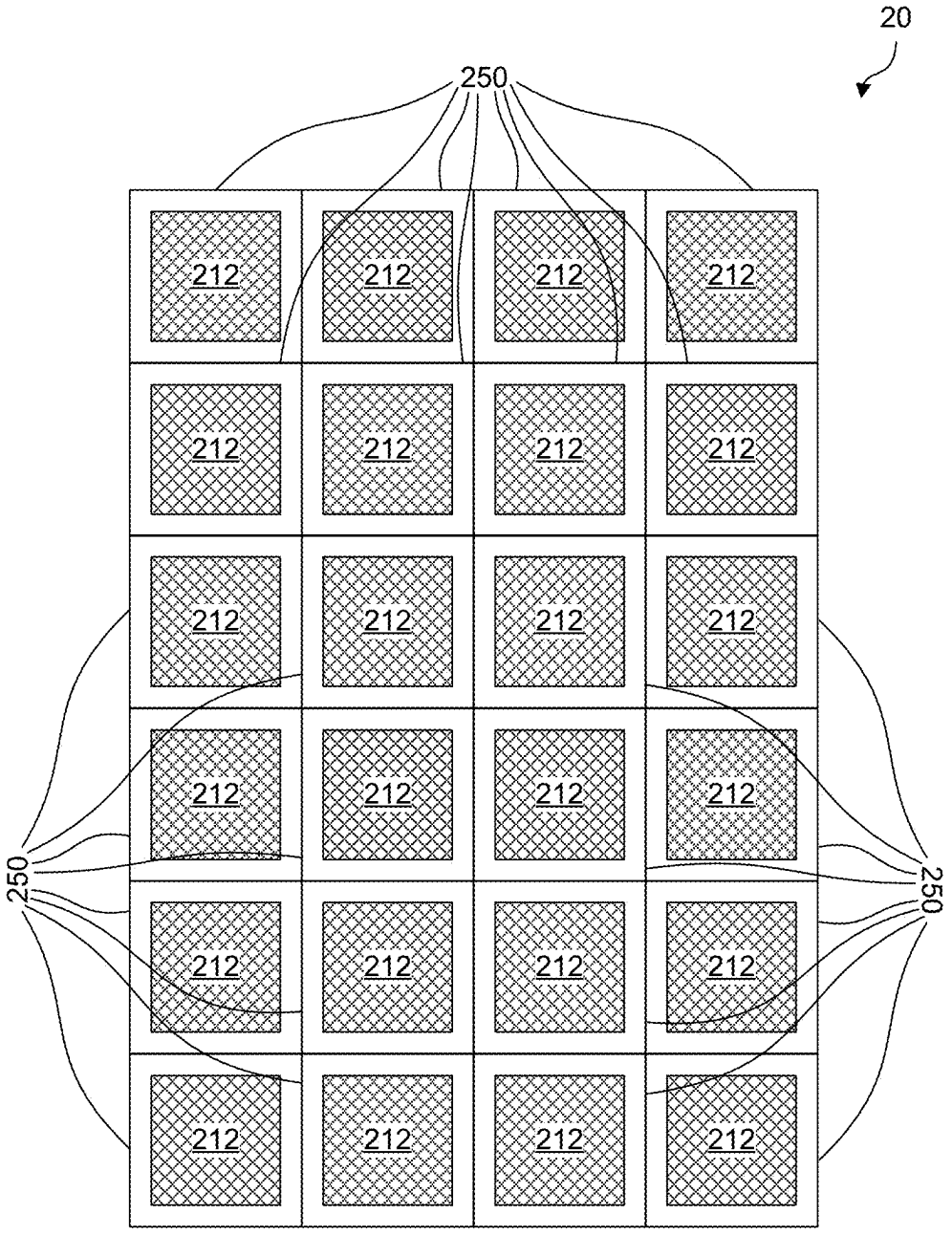
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FIG. 24

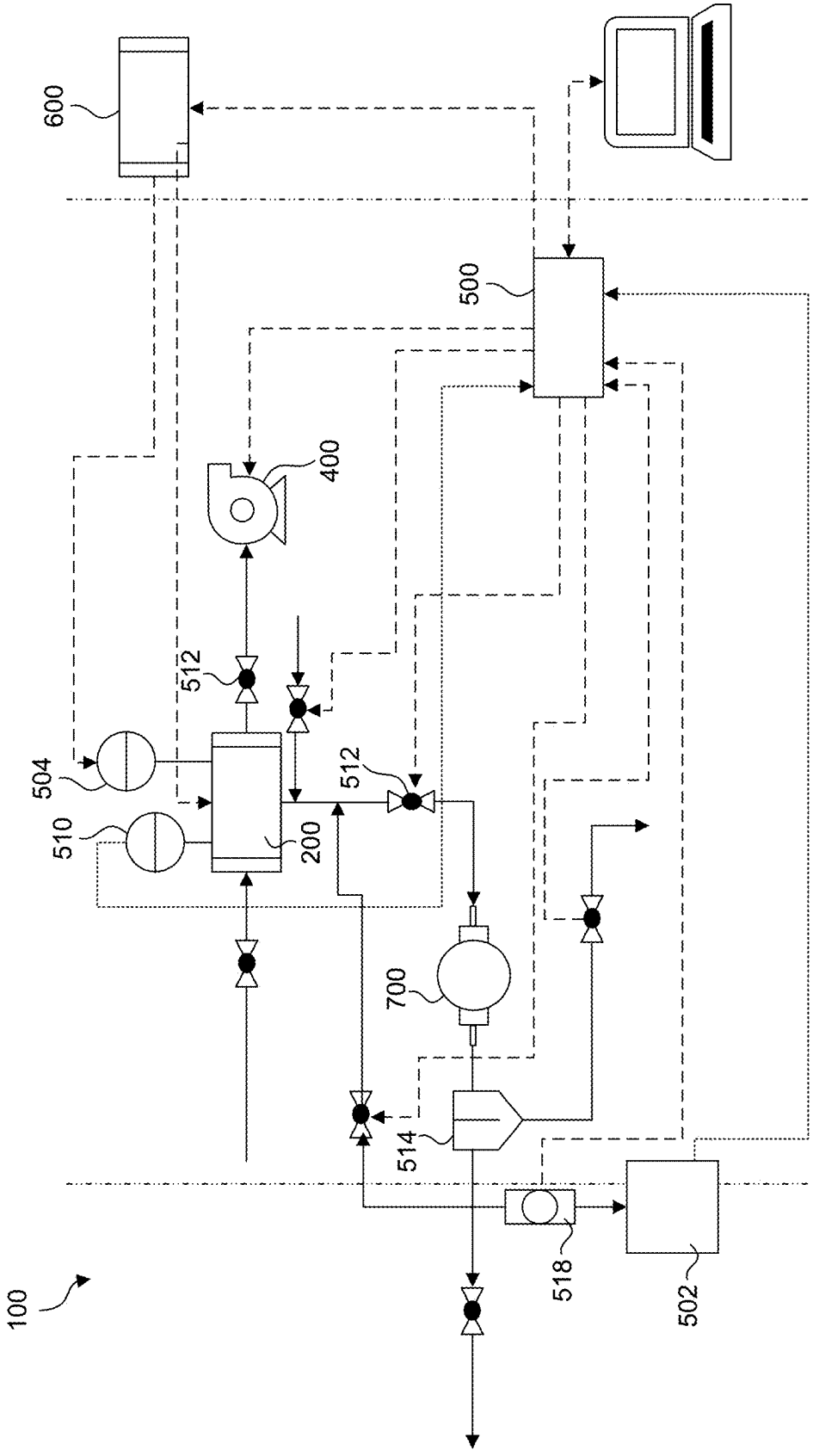

FIG. 25

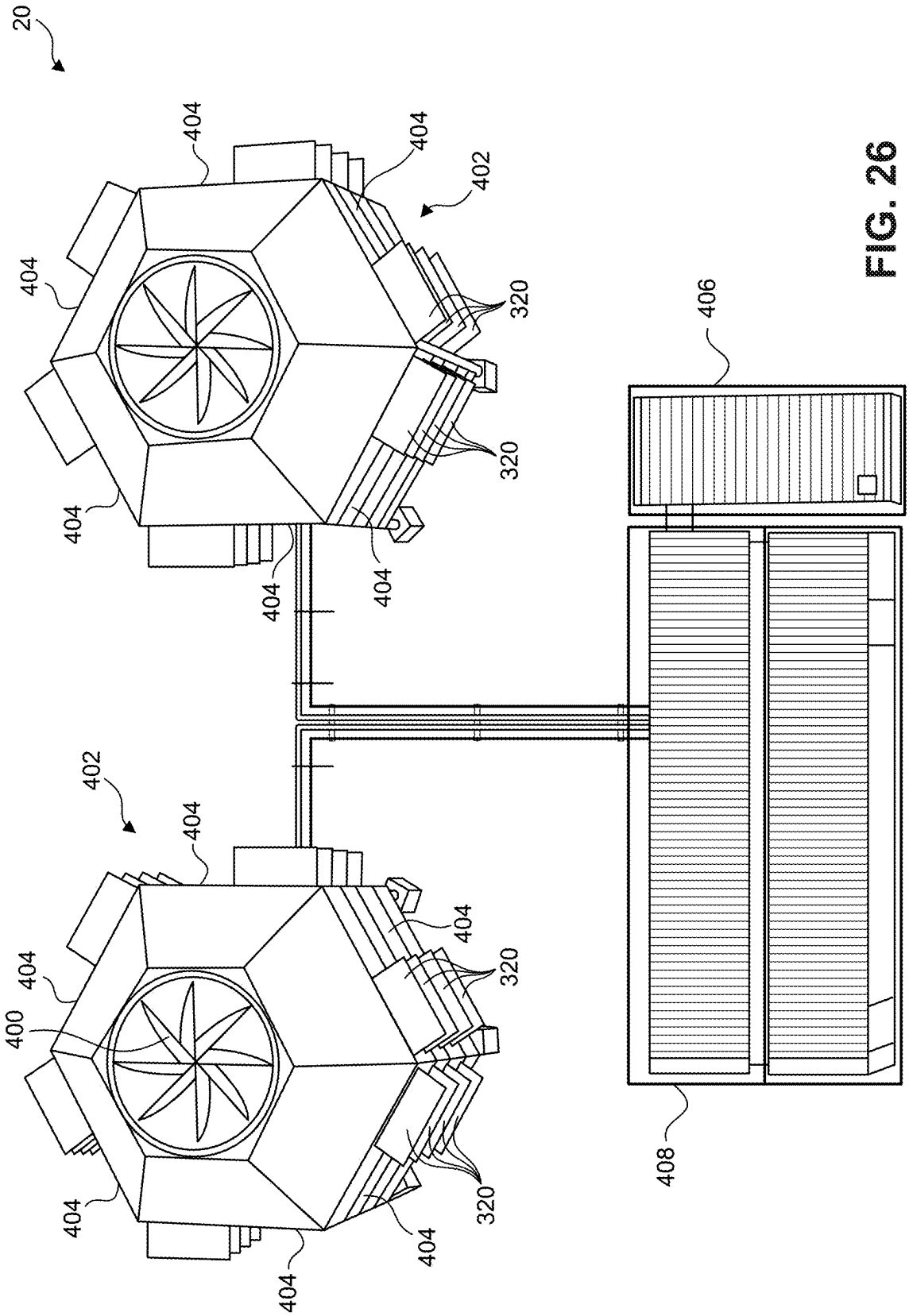
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FIG. 26

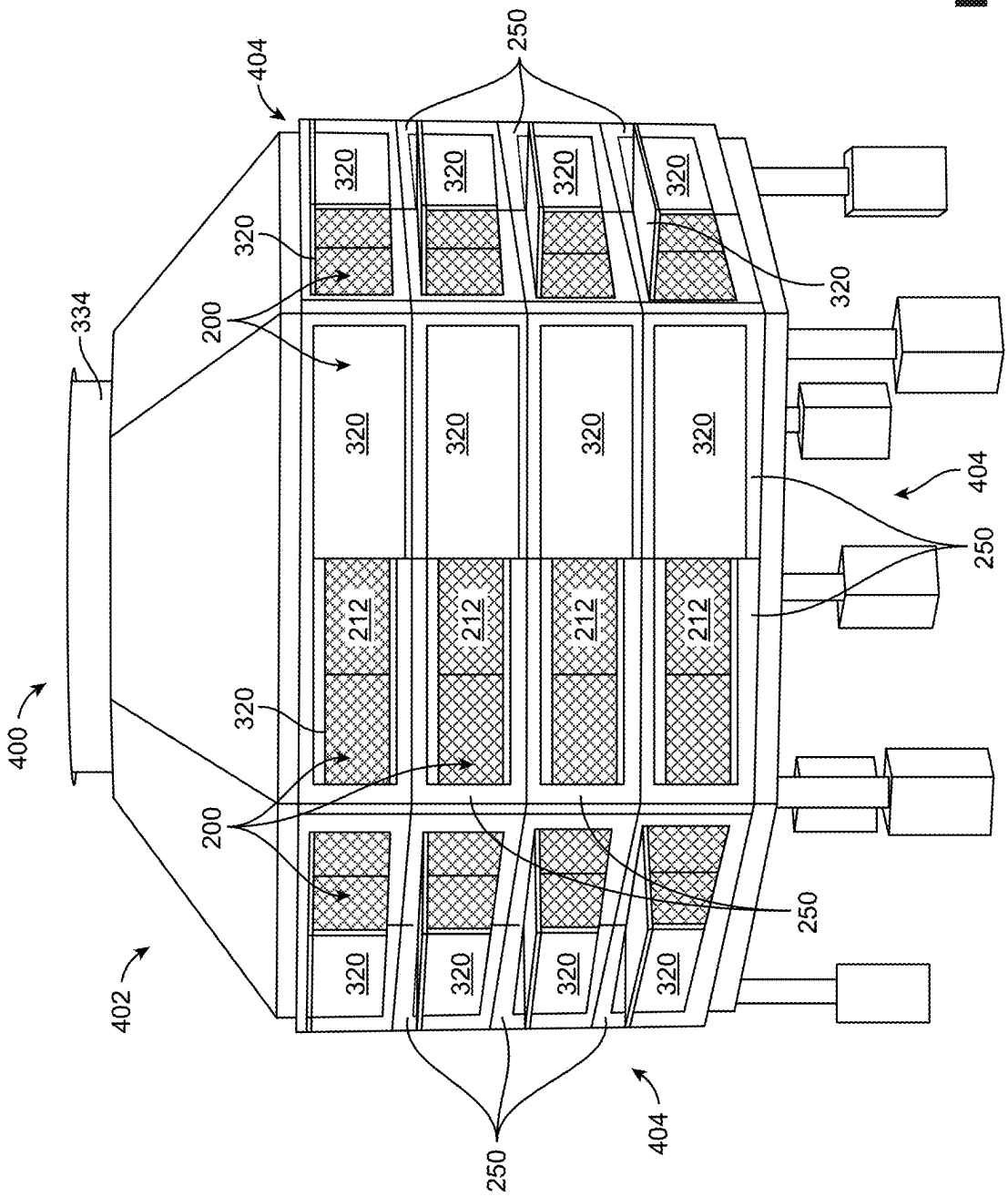
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FIG. 27

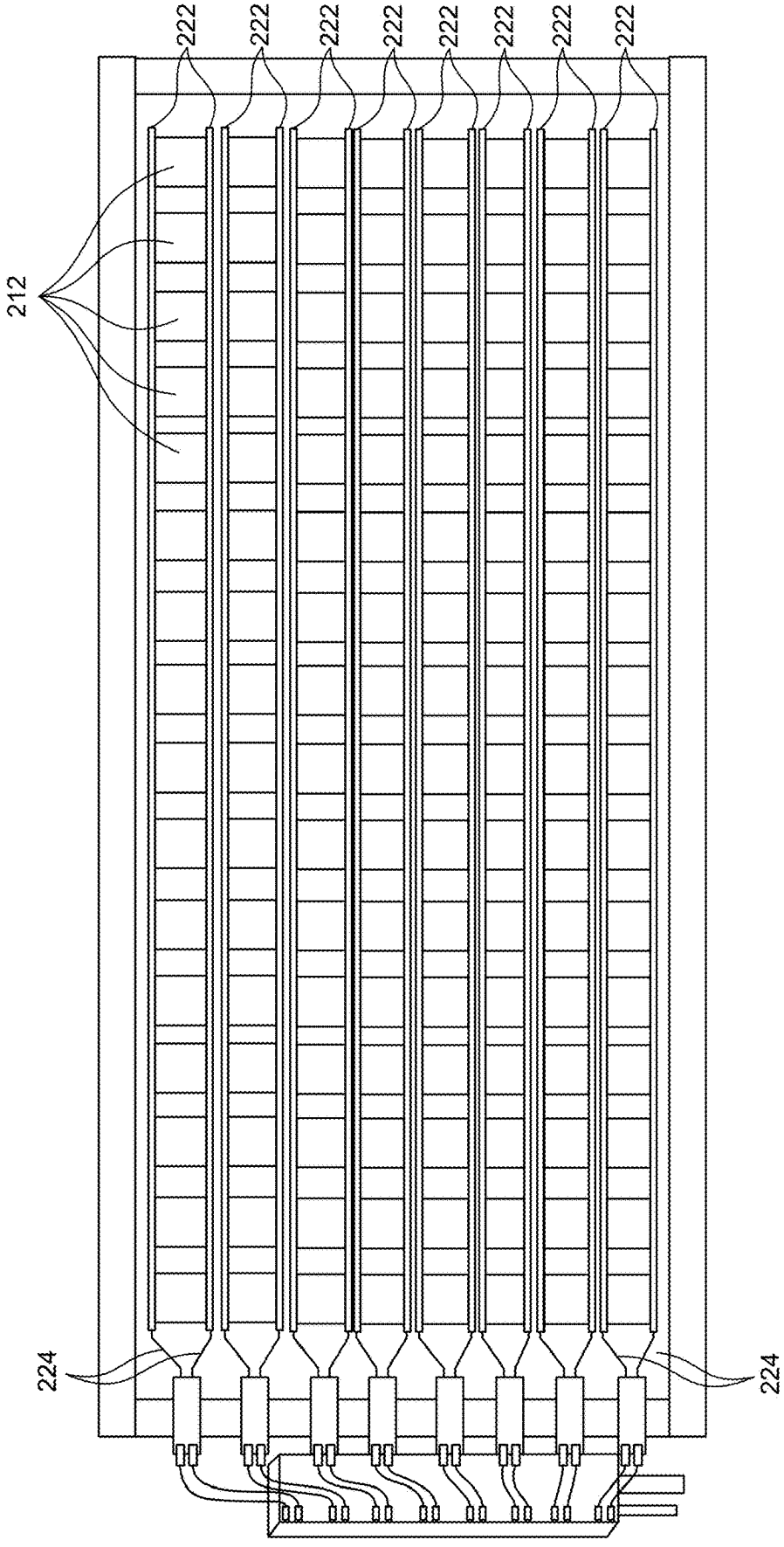

FIG. 28

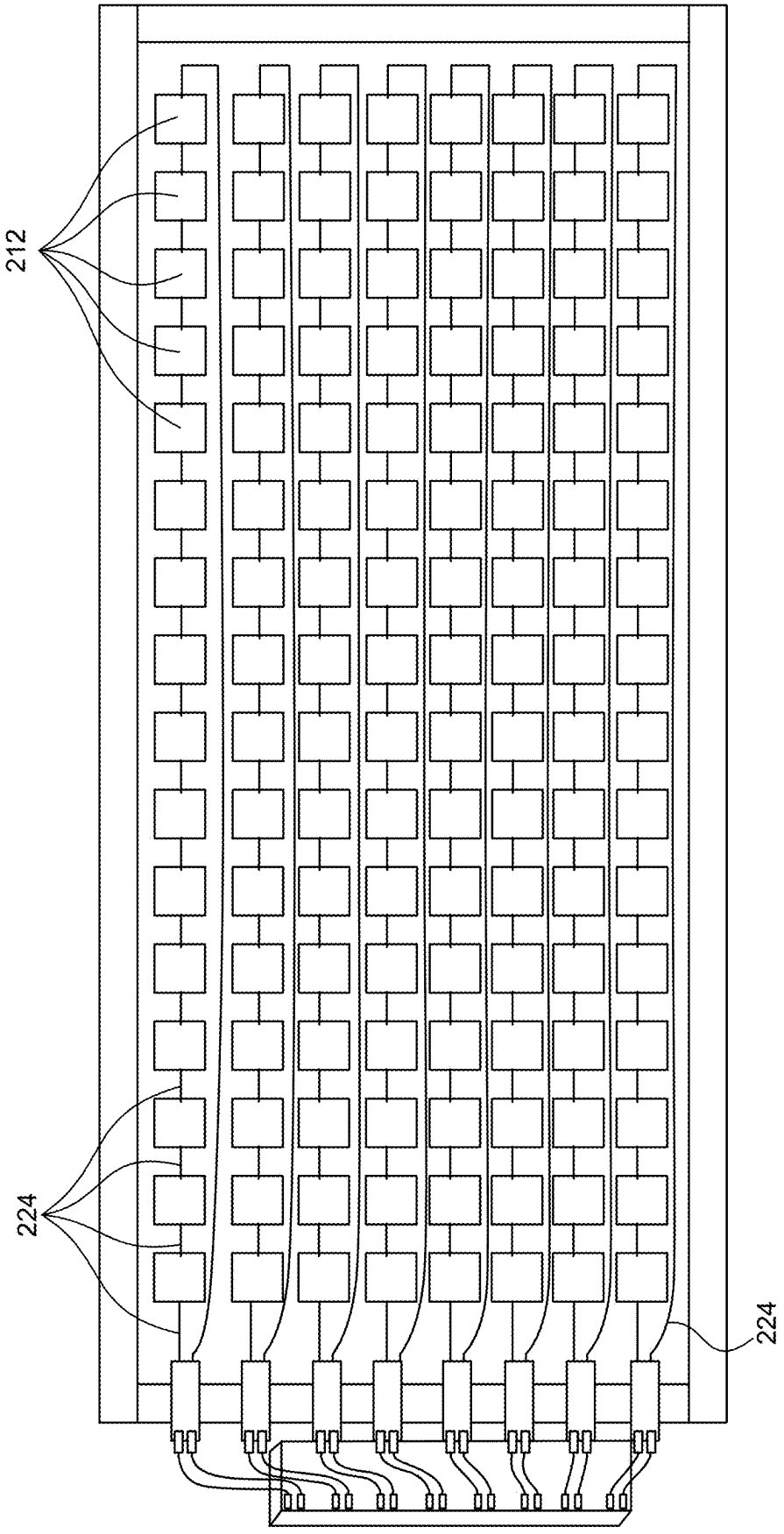

FIG. 29

SYSTEMS AND METHODS FOR REMOVING CARBON DIOXIDE FROM A FLUID

CROSS-REFERENCE

[0001] This application is a continuation of U.S. application Ser. No. 18/830,374, filed Sep. 10, 2024, which is a continuation of International Application No. PCT/US2023/070724, filed Jul. 21, 2023, which claims the benefit of U.S. Provisional Application No. 63/480,463, filed Jan. 18, 2023 and of U.S. Provisional Application No. 63/369,141, filed Jul. 22, 2022, each of which is incorporated herein in their entirety by reference thereto.

BACKGROUND

[0002] The described embodiments relate generally to systems and methods for capturing carbon dioxide from a fluid (e.g., air). More particularly, the described embodiments relate to systems and methods for adsorbing carbon dioxide from air and regenerating the adsorbed carbon dioxide to obtain carbon dioxide gas with high purity levels.

BRIEF SUMMARY

[0003] Some embodiments described herein relate to a system for extracting carbon dioxide from a fluid. In some embodiments, the system includes a fluid source and a reactor. In some embodiments, the reactor includes an inlet to receive the fluid from the fluid source, an outlet to remove the fluid from the reactor, a first chamber in fluid communication with the inlet and the outlet, a second chamber in fluid communication with the inlet and the outlet, an electric conduit, and a closure. In some embodiments, the first chamber includes a first monolith, and the first monolith includes a first sorbent to adsorb carbon dioxide. In some embodiments, the second chamber includes a second monolith, and the second monolith includes a second sorbent to adsorb carbon dioxide. In some embodiments, the electric conduit provides an electric current to the first monolith and the second monolith to release carbon dioxide adsorbed by the first monolith and the second monolith. In some embodiments, the closure moves between a first position to seal the first chamber and a second position to seal the second chamber.

[0004] In some embodiments, the conduit provides the electric current to the first monolith when the closure is in the first position and provide the electric current to the second monolith when the closure is in the second position.

[0005] In some embodiments, the electric conduit includes a first electrode coupled to a surface of the first monolith and a second electrode coupled to a surface of the second monolith, and the electric conduit provides the electric current to the first monolith and second monolith through the first electrode and the second electrode. In some embodiments, the first electrode and the second electrode are parallel to a flow direction of the fluid.

[0006] In some embodiments, the electric conduit provides the electric current to heat the first monolith and second monolith to a temperature in a range of 80° C. to 200° C. In some embodiments, the electric conduit provides the electric current to heat the first monolith and second monolith to a temperature in a range of 120° C. to 150° C. In some embodiments, the electric conduit provides the electric current to heat the first monolith and second monolith to a temperature of 150° C. in less than 30 seconds.

[0007] In some embodiments, the closure is slidable between the first position to the second position.

[0008] In some embodiments, the system also includes a first sensor to detect the carbon dioxide concentration of the fluid at the inlet and a second sensor to detect the carbon dioxide concentration of the fluid at the outlet.

[0009] In some embodiments, the closure slides based on a difference between the concentration of carbon dioxide at the inlet and the outlet.

[0010] In some embodiments, the system also includes a collector to collect carbon dioxide that is released from the first sorbent and the second sorbent.

[0011] In some embodiments, each of the first sorbent and the second sorbent includes at least one of a metal carbonate or an amine. In some embodiments, the metal carbonate compound includes at least one of potassium carbonate or calcium carbonate. In some embodiments, the amine is one of monoethylamine, glycine, sarcosine, polyethylenimine, ("PEI"), polyaziridine, linear and/or branched surfactants (e.g., lauric acid), or combinations thereof.

[0012] In some embodiments, the electric current is in a range of 0.1 A to 30 A.

[0013] In some embodiments, a difference between the pressure of the fluid at the inlet and the pressure of the fluid at the outlet is in a range of 0.2 inches of water column to 1.1 inches of water column. In some embodiments, the difference between the pressure of the fluid at the inlet and the pressure of the fluid at the outlet is about 0.5 inches of water column.

[0014] In some embodiments, the system also includes a fan to direct the fluid from the fluid source to the inlet, and fan is in fluid communication with the outlet.

[0015] In some embodiments, the fluid source is a cooling tower. In some embodiments, the fluid is a gas including carbon dioxide. In some embodiments, the fluid is ambient air.

[0016] In some embodiments, the fluid is polluted air. In some embodiments, each of the first sorbent and the second sorbent has a life of 100 cycles to 4000 cycles.

[0017] In some embodiments, the reactor also includes a first carbon dioxide outlet in fluid communication with the first chamber and a second carbon dioxide outlet in fluid communication with the second chamber. In some embodiments, the first carbon dioxide outlet removes carbon dioxide released from the first monolith, and the second carbon dioxide outlet removes carbon dioxide released from the second monolith.

[0018] In some embodiments, the system also includes a first vacuum pump in fluid communication with the first carbon dioxide outlet and a second vacuum pump in fluid communication with the second carbon dioxide outlet.

[0019] In some embodiments, the system also includes a third sensor to detect an amount of carbon dioxide at the first carbon dioxide outlet and a fourth sensor to detect an amount of carbon dioxide at the second carbon dioxide outlet.

[0020] In some embodiments, the first chamber includes a first array of monoliths, and the second chamber includes a second array of monoliths. In some embodiments, the first array of monoliths includes the first monolith, and the second array of monoliths includes the second monolith.

[0021] Some embodiments described herein relate to a method for extracting carbon dioxide from a fluid. In some embodiments, the method includes flowing the fluid from a fluid source to a first chamber, contacting the fluid with a

first sorbent disposed in the first chamber such that the first sorbent adsorbs carbon dioxide from the fluid, moving a closure to a first position to seal the first chamber, and applying electric current to the first sorbent to heat the first sorbent to a predetermined temperature to extract carbon dioxide from the first sorbent. In some embodiments, the closure is moveable between the first position that seals the first chamber and a second position that seals a second chamber. In some embodiments, the second chamber includes a second sorbent disposed in the second chamber.

[0022] In some embodiments, the method also includes flowing the fluid from the fluid source to the second chamber, when the closure is in the first position, and contacting the fluid with the second sorbent such that the second sorbent adsorbs carbon dioxide from the fluid.

[0023] In some embodiments, the applying the electric current to the first sorbent and the contacting the fluid with the second sorbent occurs simultaneously.

[0024] In some embodiments, the applying the electric current to the first sorbent is done until at least 80% of carbon dioxide has been released from the first sorbent. In some embodiments, after applying the electric current to the first sorbent, the method also includes moving the closure from the first position to the second position to unseal the first chamber and seal the second chamber, and applying electric current to the second sorbent to heat the second sorbent to the predetermined temperature to extract carbon dioxide from the second sorbent.

[0025] In some embodiments, the method also includes monitoring the concentration of carbon dioxide at the inlet, monitoring the concentration of carbon dioxide at the outlet. In some embodiments, the moving of the closure between the first position and the second position is based on a difference between the concentration of carbon dioxide at the inlet and at the outlet.

[0026] In some embodiments, the method also includes moving the closure to the second position to seal the second chamber after a time period in a range of 20 minutes to 60 minutes.

[0027] In some embodiments, the moving the closure to the first position is performed when the first sorbent is 70% to 90% saturated with carbon dioxide.

[0028] In some embodiments, the method also includes collecting the carbon dioxide extracted from the first sorbent and the second sorbent and sequestering the collected carbon dioxide.

[0029] In some embodiments, the predetermined temperature is in a range of 80° C. to 200° C. In some embodiments, the predetermined temperature is in a range of 120° C. to 180° C. In some embodiments, the predetermined temperature is 150° C. In some embodiments, the electric current is applied for 30 seconds or less (e.g., 5 seconds to 30 seconds or 20 seconds to 30 seconds) to reach the predetermined temperature.

[0030] In some embodiments, the electric current is in a range of 0.1 A to 30 A.

[0031] In some embodiments, the method also includes hermetically sealing the first chamber before applying the electric current to the first sorbent.

[0032] Some embodiments described herein relate to a reactor for extracting carbon dioxide from a fluid. In some embodiments, the reactor includes an inlet to receive a fluid including carbon dioxide, a first chamber including a first monolith to adsorb carbon dioxide from the fluid, a second chamber including a second monolith to adsorb carbon dioxide from the fluid, a closure slidably coupled to the reactor, and an electric conduit. In some embodiments, the closure slides between a first position that seals the first chamber and a second position that seals the second chamber. In some embodiments, the electric conduit applies electric current to the first monolith when the closure is in the first position to release carbon dioxide adsorbed by the first monolith and applies electric current to the second monolith when the closure is in the second position to release carbon dioxide adsorbed by the second monolith.

[0033] In some embodiments, the closure slides between the first position and the second position based on a difference between the amount of carbon dioxide at the inlet and the amount of carbon dioxide at an outlet of the reactor.

[0034] In some embodiments, the reactor also includes a first sensor to detect the carbon dioxide concentration of the fluid at the inlet and a second sensor to detect the carbon dioxide concentration of the fluid at an outlet of the reactor.

[0035] In some embodiments, each of the first monolith and the second monolith includes at least one of a metal carbonate or an amine.

[0036] In some embodiments, the metal carbonate compound includes at least one of potassium carbonate or calcium carbonate. In some embodiments, the amine is one of monoethylamine, glycine, sarcosine, polyethylenimine, ("PEI"), polyaziridine, linear and/or branched surfactants (e.g., lauric acid), or combinations thereof.

[0037] In some embodiments, the electric current is in a range of 0.1 A to 30 A.

[0038] In some embodiments, the electric conduit provides the electric current to heat the first monolith and second monolith to a temperature of 150° C. in 30 seconds or less.

[0039] In some embodiments, the reactor also includes an outlet, and a difference between a pressure of the fluid at the inlet and a pressure of the fluid at the outlet is in a range of 0.2 inches of water column to 1.1 inches of water column. In some embodiments, the difference between the pressure of the fluid at the inlet and the pressure of the fluid at the outlet is about 0.5 inches of water column.

[0040] In some embodiments, the fluid is a gas including carbon dioxide. In some embodiments, the fluid is one of ambient air or polluted air.

[0041] In some embodiments, the first chamber includes a first array of monoliths, and the second chamber includes a second array of monoliths. In some embodiments, the first array of monoliths includes the first monolith, and the second array of monoliths includes the second monolith.

[0042] Some embodiments described herein relate to a method for extracting carbon dioxide from a fluid. The method can include flowing the fluid from a fluid source to a first chamber; contacting the fluid with a first sorbent disposed in the first chamber such that the first sorbent adsorbs carbon dioxide from the fluid; moving a closure to a first position to seal the first chamber, the closure being movable between the first position that seals the first chamber and a second position that seals a second chamber, the second chamber comprising a second sorbent disposed in the second chamber; and applying electric current to the first sorbent to heat the first sorbent to a predetermined temperature to extract carbon dioxide from the first sorbent.

[0043] In some embodiments, the method includes flowing, when the closure is in the first position, the fluid from

the fluid source to the second chamber; and contacting the fluid with the second sorbent such that the second sorbent adsorbs carbon dioxide from the fluid.

[0044] In some embodiments, the applying the electric current to the first sorbent and the contacting the fluid with the second sorbent occurs simultaneously. In some embodiments, the electric current to the first sorbent is done until at least 80% of carbon dioxide has been released from the first sorbent.

[0045] In some embodiments, after applying the electric current to the first sorbent, the method further comprises moving the closure from the first position to the second position to unseal the first chamber and seal the second chamber; and applying electric current to the second sorbent to heat the second sorbent to the predetermined temperature to extract carbon dioxide from the second sorbent.

[0046] In some embodiments, the method includes monitoring the concentration of carbon dioxide at the inlet; and monitoring the concentration of carbon dioxide at the outlet. In some embodiments, the moving of the closure between the first position and the second position is based on a difference between the concentration of carbon dioxide at the inlet and at the outlet.

[0047] In some embodiments, the moving the closure to the second position to seal the second chamber after a time period in a range of 20 minutes to 60 minutes.

[0048] In some embodiments, the moving the closure to the first position is performed when the first sorbent is 70% to 90% saturated with carbon dioxide.

[0049] In some embodiments, the method includes collecting the carbon dioxide extracted from the first sorbent and the second sorbent; and sequestering the collected carbon dioxide.

[0050] In some embodiments, the predetermined temperature is in a range of 80° C. to 200° C. In some embodiments, the predetermined temperature is in a range of 120° C. to 180° C. In some embodiments, the predetermined temperature is 150° C.

[0051] In some embodiments, the electric current is applied for 30 seconds or less to reach the predetermined temperature. In some embodiments, the electric current is in a range of 0.1 A to 30 A.

[0052] In some embodiments, the method includes hermetically sealing the first chamber before applying the electric current to the first sorbent.

[0053] Some embodiments described herein relate to a reactor for extracting carbon dioxide from a fluid. In some embodiments, the reactor includes an inlet configured receive a fluid comprising carbon dioxide; a first chamber comprising a first monolith configured to adsorb carbon dioxide from the fluid; a second chamber comprising a second monolith configured to adsorb carbon dioxide from the fluid; a closure slidably coupled to the reactor, the closure configured to slide between a first position that seals the first chamber and a second position that seals the second chamber; and an electric conduit. In some embodiments, the electric conduit is configured to: apply electric current to the first monolith when the closure is in the first position to release carbon dioxide adsorbed by the first monolith; and apply electric current to the second monolith when the closure is in the second position to release carbon dioxide adsorbed by the second monolith.

[0054] In some embodiments, the closure is configured to slide between the first position and the second position based on a difference between the amount of carbon dioxide at the inlet and the amount of carbon dioxide at an outlet of the reactor.

[0055] In some embodiments, the reactor includes a first sensor configured to detect the carbon dioxide concentration of the fluid at the inlet; and a second sensor configured to detect the carbon dioxide concentration of the fluid at an outlet of the reactor.

[0056] In some embodiments, each of the first monolith and the second monolith comprises a metal carbonate. In some embodiments, the metal carbonate compound comprises at least one of potassium carbonate or calcium carbonate.

[0057] In some embodiments, the electric current is in a range of 0.1 A to 30 A. In some embodiments, the electric conduit is configured to provide the electric current to heat the first monolith and second monolith to a temperature of 150° C. in 30 seconds or less.

[0058] In some embodiments, the reactor includes an outlet. In some embodiments, a difference between a pressure of the fluid at the inlet and a pressure of the fluid at the outlet is in a range of 0.2 inches of water column to 1.1 inches of water column. In some embodiments, the difference between the pressure of the fluid at the inlet and the pressure of the fluid at the outlet is about 0.5 inches of water column.

[0059] In some embodiments, the fluid is a gas comprising carbon dioxide. In some embodiments, the fluid is one of ambient air or polluted air.

[0060] In some embodiments, the first chamber comprises a first array of monoliths, and the second chamber comprises a second array of monoliths, and wherein the first array of monoliths comprises the first monolith, and the second array of monoliths comprises the second monolith.

[0061] Some embodiments described herein relate to a modular system comprising a plurality of reactors. In some embodiments, a first reactor of the plurality of reactors is the reactor according to any of the embodiments described herein.

[0062] In some embodiments, the first reactor is removably coupled to a second reactor of the plurality of the reactors.

[0063] In some embodiments, the modular system comprises a duct coupled to each of the plurality of reactors.

[0064] Some embodiments described herein relate to a method of making a carbon monolith. In some embodiments, the method includes mixing carbon with at least one of a binder or an additive to form a mixture; extruding the mixture to form a monolith structure; drying the monolith structure to a moisture content of 0 w % to about 10 wt %; calcining the monolith structure; soaking the monolith structure in an aqueous solution, the aqueous solution comprising a metal; flowing air over the monolith structure to remove excess liquid from the monolith structure; heating the monolith structure using an alternating current joule heating. In some embodiments, the binder comprises one or more of a silicate solution, whey, baking flour, bentonite, natural clays, synthetic clays, or combinations thereof. In some embodiments, the additive comprises one or more of graphite, formaldehyde, resorcinol, carbon fiber, carbon nanotubes, carbon nanofibers, nanodiamonds, buckyballs, pure or ligated metal (e.g., copper, aluminum, iron, gold, platinum, palladium, silver), nanoparticles or oxides thereof, zeolites, metal-organic frameworks, covalent organic frameworks,

natural or synthetic silicas, polyamine polymers, polyethylene glycol, amino acids, a single or mixture of metal carbonate salts, or combinations thereof.

[0065] Some embodiments described herein relate to a reactor for extracting carbon dioxide from a fluid. In some embodiments, the reactor includes an inlet configured receive a fluid comprising carbon dioxide; an outlet configured to remove the fluid from the reactor; a chamber comprising a monolith configured to adsorb carbon dioxide from the fluid; a first closure hingedly coupled to the inlet and configured to move between a closed position and an open position, wherein the first closure seals the inlet in the closed position; an electric conduit configured to apply electric current to the monolith when the first closure is in the closed position.

[0066] In some embodiments, the reactor includes a second closure hingedly coupled to the outlet and configured to move between a closed position and an open position, wherein the second closure seals the outlet in the closed position.

[0067] In some embodiments, the reactor includes a first hydraulic cylinder configured to move the first closure between the closed position and the open position, and a second hydraulic cylinder configured to move the second closure between the closed position and the open position. In some embodiments, the first hydraulic cylinder is configured to move the first closure between the first position and the second position based on a difference between the amount of carbon dioxide at the inlet and the amount of carbon dioxide at the outlet.

[0068] In some embodiments, the reactor includes a first clamp configured to secure the first closure in the closed position; and a second clamp configured to secure the second closure in the closed position.

[0069] In some embodiments, the reactor comprises a first sensor configured to detect the carbon dioxide concentration of the fluid at the inlet.

[0070] In some embodiments, the outlet is configured to be coupled to a duct, the duct comprising a fan configured to direct the fluid through the inlet.

[0071] In some embodiments, the monolith comprises a metal carbonate. In some embodiments, the metal carbonate compound comprises at least one of potassium carbonate or calcium carbonate.

[0072] In some embodiments, the electric current is in a range of 0.1 A to 30 A.

[0073] In some embodiments, the electric conduit is configured to provide the electric current to heat the monolith to a temperature of 150° C. in 30 seconds or less.

[0074] In some embodiments, a difference between a pressure of the fluid at the inlet and a pressure of the fluid at the outlet is in a range of 0.2 inches of water column to 1.1 inches of water column. In some embodiments, the difference between the pressure of the fluid at the inlet and the pressure of the fluid at the outlet is about 0.5 inches of water column.

[0075] In some embodiments, the chamber comprises an array of monoliths, and wherein the first array of monoliths comprises the first monolith.

[0076] Some embodiments described herein relate a modular system comprising a plurality of reactors. In some embodiments, a first reactor of the plurality of reactors is the reactor of any of the embodiments described herein. In some embodiments, the first reactor is removably coupled to a second reactor of the plurality of reactors.

[0077] Some embodiments described herein relate to a modular system. In some embodiments, the modular system comprises a plurality of reactors includes a first reactor and a second reactor. In some embodiments, the first reactor includes an inlet configured to receive a fluid from a fluid source; a monolith comprising a sorbent configured to adsorb carbon dioxide; an electric conduit configured to provide an electric current to the monolith to release carbon dioxide adsorbed by the monolith; and a closure configured to move between a first position to a second position, wherein the closure is configured to seal the inlet in the first position. In some embodiments, the first reactor is removably coupled to the second reactor.

[0078] In some embodiments, the second reactor includes an inlet configured to receive the fluid from the fluid source; a monolith comprising a sorbent configured to adsorb carbon dioxide; an electric conduit configured to provide an electric current to the monolith to release carbon dioxide adsorbed by the monolith; and a closure configured to move between a first position to a second position, wherein the closure is configured to seal the inlet in the first position.

[0079] In some embodiments, the first reactor is stacked on the top of the second reactor.

[0080] In some embodiments, the first reactor is disposed horizontally next to the second reactor.

[0081] In some embodiments, the modular system includes a fan configured to direct the fluid through the inlet of the first reactor and the inlet of the second reactor.

[0082] In some embodiments, the modular system includes a control unit coupled to the first reactor and the second reactor.

[0083] In some embodiments, the modular system includes a carbon dioxide purification unit coupled to the first reactor and to the second reactor.

BRIEF DESCRIPTION OF THE FIGURES

[0084] FIG. **1** illustrates a system for extracting carbon dioxide according to some embodiments.

[0085] FIG. **2**A illustrates a monolith in contacting mode according to some embodiments.

[0086] FIG. **2**B illustrates a monolith in regeneration mode according to some embodiments.

[0087] FIG. **3** illustrates an array of monoliths according to some embodiments.

[0088] FIG. **4** illustrates a monolith according to some embodiments.

[0089] FIG. **5** illustrates an electrical system used with monoliths according to some embodiments.

[0090] FIG. **6** illustrates a reactor according to some embodiments.

[0091] FIG. **7** illustrates a reactor according to some embodiments.

[0092] FIG. **8** illustrates a reactor according to some embodiments.

[0093] FIG. **9** illustrates a reactor according to some embodiments used with a cooling tower according to some embodiments.

[0094] FIG. **10** illustrates a reactor according to some embodiments used with a cooling tower according to some embodiments.

[0095] FIG. **11** illustrates the amount of carbon dioxide adsorbed over cycles.

[0096] FIG. **12** is a chart showing sorbent capacity in relation to cycle numbers according to some embodiments.
[0097] FIG. **13** illustrates an electrical system for multiple arrays of monoliths according to some embodiments.
[0098] FIG. **14**A illustrates an electrical system for monoliths configured in parallel.
[0099] FIG. **14**B illustrates an electrical system for monoliths configured in series.
[0100] FIG. **15** illustrates a method for extracting carbon dioxide according to some embodiments.
[0101] FIG. **16** illustrates a method for extracting carbon dioxide according to some embodiments.
[0102] FIG. **17** illustrates a diagram showing electrode-solution interfaces according to some embodiments.
[0103] FIGS. **18**A-**18**C illustrate the interaction of ions at the interface between electrodes and monoliths according to some embodiments.
[0104] FIG. **19** illustrates frequency of heating according to various methods.
[0105] FIG. **20** illustrates a flowchart of a method according to some embodiments.
[0106] FIG. **21** illustrates a flowchart of a method according to some embodiments.
[0107] FIG. **22** illustrates a reactor according to some embodiments.
[0108] FIG. **23** illustrates a reactor according to some embodiments.
[0109] FIG. **24** illustrates a system of reactors according to some embodiments.
[0110] FIG. **25** illustrates a schematic of a system for extracting carbon dioxide according to some embodiments.
[0111] FIG. **26** illustrates a system of reactors according to some embodiments.
[0112] FIG. **27** illustrates a system of reactors according to some embodiments.
[0113] FIG. **28** illustrates an array of monoliths connected in series according to some embodiments.
[0114] FIG. **29** illustrates an array of monoliths connected in parallel according to some embodiments.

DETAILED DESCRIPTION

[0115] A significant portion of greenhouse gas emissions comes from carbon dioxide that is released into the atmosphere from numerous sources, including from HVAC systems, refrigeration systems, and industrial processes; land changes (e.g., deforestation); and burning fossil fuels, which can contribute to issues related to climate change. Often emissions are moved through cooling towers. Reducing carbon dioxide in the atmosphere is a priority across many governments and industries. One way to reduce carbon dioxide emissions is to avoid emissions altogether, but complete elimination of emissions is often impossible, impractical, or requires significant modifications and/or capital improvements to modify existing systems and processes.
[0116] Another way to reduce carbon dioxide in the atmosphere is removing carbon dioxide from emissions from various sources described above, for example by capturing carbon dioxide from emissions or from the air or from cooling towers moving air. However, there are several challenges related to capturing carbon dioxide, and existing systems are often difficult to implement at large scale.
[0117] For example, existing systems may be complicated systems with multiple components spread across different portions of the system. Such a system often needs significant modifications and/or capital improvements to implement carbon capture systems. Moreover, some retrofit carbon dioxide capture systems can interfere with the normal performance of equipment to which they are added, either as a result of the upfront modification or due to the limited capacity or efficiency of existing carbon dioxide capturing systems. Lastly, existing systems often use significant amounts of raw materials, fresh water, and energy, which can counteract the targeted environmental benefits.
[0118] Embodiments disclosed herein overcome these and other challenges by providing-among other benefits-systems and methods for capturing carbon dioxide at the point of emission or from the atmosphere that can be efficiently integrated into existing industrial equipment. Moreover, embodiments disclosed herein can not only remove carbon dioxide from a fluid stream but also adsorb the carbon dioxide for later regeneration and eventually sequestration. In some embodiments, a system (e.g., system **10**) integrates carbon dioxide separation and collection. In some embodiments, the system can be easily integrated into existing systems (e.g., cooling towers), which can reduce capital cost and installation time. In some embodiments, the system is modular. Modularity can allow the system to be built quickly, make the system easily adaptable to different site conditions, allow for rapid scaling up and scaling down, and lower the cost for packaging and shipping. Moreover, systems disclosed herein can integrate with systems, such as cooling towers, without significantly impacting performance of the systems.
[0119] FIG. **1** illustrates a flow chart for a carbon dioxide capturing system (e.g., system **10**) according to some embodiments. In some embodiments, system **10** includes fluid source **100**, reactor **200** having contactor mode **202** and regenerator mode **204**, and power source **600**.
[0120] In some embodiments, fluid source **100** provides fluid **102** to reactor **200** through inlet stream **101**. In some embodiments, fluid **102** includes a greenhouse gas (e.g., carbon dioxide). Although system **10** is described throughout as removing carbon dioxide from a fluid, it is to be understood that system **10** could be used to remove other gases or contaminants, such as other greenhouse gases. In some embodiments, fluid **102** is ambient air. In some embodiments, ambient air is non-polluted air processed by sources such as HVAC systems and refrigeration systems. In some embodiments, fluid **102** includes polluted air. In some embodiments, polluted air is air containing elevated levels of hazardous or toxic components, such as particulate matter or volatile organic compounds. In some embodiments, fluid source **100** includes a cooling tower and fluid **102** is the emissions from the cooling tower. In some embodiments, fluid source **100** is fluid to be passed through a cooling tower. In some embodiments, fluid **102** can be a gas other than air. In some embodiments, fluid **102** can be a mixture of different gasses. In some embodiments, system **10** can be integrated into existing systems, such as cooling towers (e.g., cooling tower **800**). Cooling towers already flow large amounts of fluid, for example air, so integrating system **10** into cooling towers reduces energy consumption and land use. However, it is to be understood that some embodiments can also be integrated into other industrial systems and equipment, such as a point of emission in a power plant.
[0121] In some embodiments, system **10** includes reactor **200**. In some embodiments, reactor **200** can be an integral

reactor that can perform different stages of the carbon dioxide capturing process, such as adsorption and regeneration. This can reduce the total size requirements for the carbon dioxide capturing system and make it readily compatible with various industrial equipment. In some embodiments, as discussed in more detail below, reactor **200** can operate continuously by having multiple chambers to simultaneously perform adsorption and regeneration. This can increase the efficiency of the capturing process. In some embodiments, the assembly is designed to minimize the pressure drop or velocity change of the air flowing through reactor **200**, thereby minimizing the interference with a normal operation of the equipment in which system **10** can be integrated. In some embodiments, as discussed in detail below, reactor **200** can include a solid monolith for adsorption. In some embodiments, as discussed in detail below, reactor **200** uses an energy efficient regeneration process.

[0122] In some embodiments, reactor **200** includes one or more contactors **202** and one or more regenerators **204** disposed within reactor **200**. In some embodiments, contactor **202** and regenerator **204** are separate structures within reactor **200**, and in some embodiments, contactor **202** and regenerator **204** make an integral structure within reactor **200**. In some embodiments, reactor **200** can include inlet stream **101**, first product stream **103**, and second product stream **105**. In some embodiments, reactor **200** includes one or more monoliths **212**. In some embodiments, monolith **212** is an activated carbon monolith impregnated with a sorbent material (e.g., sorbent **214**). In some embodiments, sorbent **214** can adsorb carbon dioxide. In some embodiments, fluid **102** from fluid source **100** can flow into reactor **200** through inlet stream **101** and contact monolith **212**. In some embodiments, when fluid **102** contacts monolith **212**, monolith **212** can adsorb carbon dioxide from fluid **102**, and the remaining fluid **104** (e.g., fluid **102** less carbon dioxide) exits reactor **200** through first product stream **103**.

[0123] Reactor **200** can include an array of monoliths (e.g., array **210** of monoliths **212**), as shown in FIGS. **3** and **6-8**. Array **210** can include a grid pattern of monoliths **212**. As shown in FIG. **3**, array **210** can include multiple rows of monoliths **212** in series with electrodes **220** between each row of monoliths **212**. Each row of monoliths **212** can be arranged in parallel to each other, as shown in FIG. **4**. In some embodiments, array **210** is an array having dimensions a×b, where a is an integer from 1 to 250 and b is an integer from 1 to 250. In some embodiments, array **210** can have between 100 monoliths and 50,000 monoliths (e.g., between 1000 monoliths and 30,000 monoliths or between 10,000 monoliths and 20,000 monoliths). Each monolith **212** can have a length in a range of about 4 inches to about 20 inches, a width in a range of about 4 inches to about 20 inches, and a height in a rage of about 4 inches to about 20 inches. In some embodiments, each monolith includes 100 cells per square inch with 100 cells per square inch. For example, in some embodiments, a monolith having a width of 10 inches and a height of 10 inches can have 10,000 cells (e.g., cells **213**).

[0124] For example, FIG. **6** illustrates reactor **200** having a 1×2 array (e.g., array **210**) of monoliths (e.g., monoliths **212***a* and **212***b*); FIG. **7** illustrates reactor **200** having a 12×6 array of monoliths; and FIG. **8** illustrates reactor **200** having a 10×11 array of monoliths. In some embodiments, reactor **200** includes one or more closures **300** and/or closures **320**. In some embodiments, reactor **200** includes housing **302**, frame **304** defining an opening, and F disposed around opening **204**.

[0125] In some embodiments, after monolith **212** is saturated with carbon dioxide, regenerator **204** can heat monolith **212** (e.g., using electric current **602** provided by power source **600**) to release the adsorbed carbon dioxide in monolith **212**. Heating monolith **212** is discussed in more detail below. In some embodiments, the released carbon dioxide exits reactor as carbon dioxide-rich stream **106** through second product stream **105**.

[0126] In some embodiments, fluid **102** flows through reactor **200** and contacts at least one monolith **212**. In some embodiments, reactor **200** includes at least one monolith **212**. In some embodiments, reactor **200** includes an array **210** of monoliths **212**. In some embodiments, monolith **212** adsorbs carbon dioxide from fluid **102**. In some embodiments, monolith **212** is a solid. In some embodiments, after monolith **212** adsorbs carbon dioxide, fluid **104** (e.g., fluid **102** less carbon dioxide) exits reactor **200** through product stream **103**. In some embodiments, fluid **104** is released to the atmosphere. In some embodiments, reactor **200** is disposed at an inlet to a cooling tower, and fluid **104** exits reactor and is used for the original purposes of fluid source **100**, such as a cooling media in a cooling tower.

[0127] In some embodiments, after monolith **212** is saturated with carbon dioxide, carbon dioxide is released from monolith **212**. In some embodiments, power source **600** applies energy to monolith **212** to regenerate the adsorbed carbon dioxide. In some embodiments, power source **600** applies electric energy to cause joule heating of sorbent **214** to regenerate the adsorbed carbon dioxide. In some embodiments, extracted carbon dioxide-rich stream **106** exists regenerator **204** and reactor **200** for collection. In some embodiments, extracted carbon dioxide-rich stream exits regenerator **204** and reactor **200** through second product stream **105**. In some embodiments, carbon dioxide-rich stream **106** comprises at least 90% carbon dioxide by volume (e.g., at least 95% carbon dioxide by volume or at least 99% carbon dioxide by volume. In some embodiments, carbon dioxide-rich stream **106** is sequestered for permanent removal from the atmosphere. In some embodiments, after regeneration, as discussed in detail below, monolith **212** can be re-used for additional adsorption and regeneration processes.

[0128] Each monolith **212** within reactor **200** can adsorb and desorb (e.g., release) carbon dioxide. The adsorption occurs when monolith **212** is in "contacting" mode, and desorption occurs when monolith **212** is in "regeneration" mode. FIG. **2**A illustrates the operation of system **10** as monolith **212** adsorbs carbon dioxide in contacting mode, and FIG. **2**B illustrates the operation of system **10** when monolith **212** has been saturated and carbon dioxide is released in regeneration mode. In some embodiments, fluid **102** passes through monolith **212** to adsorb carbon dioxide from fluid **102**. In some embodiments, system **10** includes fan **400** that pulls fluid **102** from fluid source **100** through monolith **212**. In some embodiments, as shown in FIG. **2**A, fan **400** is provided in fluid communicate with monolith **212** downstream of monolith **212**. As illustrated in FIG. **2**B, adsorbed carbon dioxide can be release from monolith **212** by applying electric current **602** (e.g., from power source **600**) to monolith. In some embodiments, system **10** includes

vacuum pump **700** downstream of monolith **212** to pull carbon dioxide-rich stream **106** from reactor **200**.

[0129] As illustrated in FIGS. **3-5**, monolith **212** can have various configurations of electrodes **220** that supply electric current **602** to monolith **212** depending on the specific equipment set up and energy needs of the system. In some embodiments, power source **600** applies electric current **602** to monolith **212**. FIG. **4** illustrates a monolith **212** with electrodes **220** contacting side surfaces of monolith **212**. In some embodiments, electrodes **220** are adhered to monolith **212**. In some embodiments, electrodes **220** are adhered to monolith **212** using a conductive adhesive (e.g., a carbon fiber conductive adhesive). In some embodiments, electrodes **220** are oriented parallel to the direction of the flow fluid **102**.

[0130] In some embodiments, as described in more detail below, the electric current **602** heats monolith **212** to release carbon dioxide from monolith **212**. In some embodiments, electric current **602** heats monolith **212** to a range of about 60° C. to about 200° C. (e.g., about 80° C. to about 180° C., about 120° C. to about 150° C.). In some embodiments, electric current **602** heats monolith **212** to a temperature of about 150° C.

[0131] In some embodiments, monolith **212** is heated by joule heating, which increases efficiency of the system, especially at the temperatures required for efficient release of carbon dioxide. Although the monolith can be heated by other means, these often come with various drawbacks. For example, convection heating uses a condensable gas (e.g., steam) to separate streams. Typically very high temperature steam is required to achieve acceptable rates for carbon dioxide release. This results in an expensive, energy intensive process. Moreover, convection can increase impurities in the carbon dioxide that is removed from the fluid (e.g., fluid **102**). Although a lower-temperature steam could be used, which could reduce energy requirements, steam at lower temperatures can take significantly longer to release carbon dioxide (e.g., on the order of hours). Conduction heating is also less efficient because the rate of release of carbon dioxide is limited by the coefficient of heat transfer of sorbent **214**, which in most cases is not suitable for rapid release of carbon dioxide. Radiation heating is challenging to apply to internal areas of a reactor, making it unsuitable for applications disclosed herein. Lastly, induction heating requires special doping of the monolith and large volumes of the doping materials. Accordingly, the present inventors have found that joule heating provides relatively low energy heating with rapid release of carbon dioxide.

[0132] In some embodiments, power source **600** provides electric current **602** to cause joule heating of monolith **212**. Joule heating applies electric current though monoliths **212** to cause electrons collide with atoms within monolith **212**, thereby releasing energy in the form of heating. Joule heating as discussed herein is more rapid and improves energy use compared to traditional heating methods. First, joule heating does not require heat transfer, so it eliminates any inefficiencies or heat losses resulted from heat transfer, thereby allowing a more rapid heating.

[0133] FIG. **11** illustrates the rise of temperature of a monolith (e.g. monolith **212**) over time using joule heating. As shown in FIG. **11**, joule heating according to embodiments described herein can achieve temperatures of 80° C. in about 5 seconds, temperatures of about 120° C. in about 20 seconds, and temperatures of about 150° C. in about 30 seconds. Additionally, unlike other heating methods like those discussed above, joule heating increases the temperature locally, for example, where electric current is applied. This further minimizes unnecessary energy consumption.

[0134] In some embodiments, monolith **212** is heated by joule heating to a temperature at which regeneration (e.g., carbon dioxide release) typically begins (e.g. approximately 80° C.) in less than 10 seconds (e.g., about 5 second to about 10 seconds). In some embodiments, monolith **212** is heated by joule heating to a temperature of 80° C. in about 5 seconds.

[0135] FIGS. **3** and **4** show the setup of monolith **212** for regeneration according to various embodiments. Electrodes **220** are attached to surfaces of monolith **212**, and power source **600** applies electric current to monolith **212** through electrodes **220**. In some embodiments, electrodes **220** are provided on the sides of monolith **212** parallel to the flow direction of fluid **102**, such that electrodes **220** do not obstruct the flow of fluid **102**. In some embodiments, electrodes **220** are provided on two sides of monolith **212**, as illustrated in FIGS. **3** and **4**. In some embodiments, electrodes **220** are provided on four sides of monolith, as illustrated in FIG. **5**. In some embodiments, electrodes **220** are pairs of bipolar electrodes.

[0136] In some embodiments, power source **600** applies electric current through a circuit. In some embodiments, the circuit can have a switch **604** to selectively apply electric current to specific electrodes. For example, as shown in FIG. **5**, when switch **604** is at position A, electrodes **220** on the left and right sides of monolith **212** are activated, thereby applying a current through monolith **212** in a horizontal direction; when switch **604** is at position B, electrodes **220** on the top and bottom sides of monolith **212** are activated, thereby applying a current through monolith **212** in a vertical direction. In some embodiments, switch **604** can alternate between position A and position B to cause alternating heating between horizontal and vertical directions, thereby improve the homogeneity of temperature within monolith **212**. FIG. **13** shows a set of up of an array of monoliths for regeneration according to some embodiments.

[0137] In some embodiments, power source **600** applies alternating current through monolith **212** between two electrodes **220**. In some embodiments, monolith **212** is coated with a material that forms a solid-state electrolytic cell with metal electrodes (e.g., electrodes **220**). Alternating current can be applied with a high frequency to reduce ionic migration within monolith **212** and interfacial redox reactions with electrodes **220**. For example, the alternating current frequency can be in a range of about 2 kHz to about 200 kHz. In some embodiments, the alternating current frequency is in a range of about 2 kHz to about 200 kHz (e.g., about 50 kHz to about 150 kHz, or about 75 kHz to about 125 kHz). In some embodiments, the alternating current frequency is about 100 kHz.

[0138] High frequency alternating current used with embodiments discussed herein can improve the lifetime of monolith **212**. For example, the alternation of the direction of current can outpace the harmful electrochemical processes that would have occurred within monolith **212** between two electrodes **220**, thereby increasing the efficiency and lifetime of monolith **212**. In some embodiments, when a high frequency alternating current is used (e.g. 2 kHz to 100 kHz), the lifetime of monolith **212** can be significantly increased. For example, when direct current is used,

monolith **212** may have a lifetimes around 5 cycles. In contrast, when high frequency alternative current is used, monolith **212** can have a lifetime of about 1000 cycles to about 4000 cycles (e.g., about 1500 cycles). As used herein, a "cycle" includes heating monolith **212** to regeneration temperatures (e.g. about 75° C. to about 300° C. or about 130° C.) and cooling monolith **212** to ambient temperature (e.g. about −20° C. to about 32° C.).

[0139] Additionally, heating efficiency can be improved by using high frequency alternating current. For example, when a high frequency alternating current is used (e.g. 2 kHz to about 100 kHz), it can prevent the formation of an Electron Double Layer Capacitor (EDLC) forming at the interface between monolith **212** and electrodes **220**. Accordingly, the monolith-electrode cell can behave as a pure resistor, which can bring improved heating efficiency. FIGS. **18**A-C illustrate the interaction at the interface of monolith **212** and electrodes **220**. As shown in FIG. **18**A, EDLC can form at the interface between monolith **212** and electrodes **220** when the alternating current frequency is low (e.g. about 1 Hz to about 2 kHz). When the frequency is increased to an optimized zero-phase frequency (e.g. about 2 kHz to about 110 kHz), as illustrated by FIG. **18**B, the phase angle between voltage and current waveforms becomes zero, and no EDLC is formed at the interface between monolith **212** and electrodes **220**. Further, as illustrated in FIG. **18**C, at higher frequencies with heating restrained (e.g. more than about 110 kHz), no EDLC is formed. The EDLC formed at low frequency (e.g. about 1 Hz to about 2 kHz) can cause at least two issues with functionality. First, EDLC formation can cause deposition of sorbent from monolith **212**, which can cause high resistance at the interface between monolith **212** and electrodes **220**. Second, EDLC formation can cause sorbent migration within monolith **212** that can cause non-homogenous resistance, which in turn can cause uneven temperature distribution within monolith **212**.

[0140] In some embodiments, electrodes **22** are carbon-coated electrodes. In some embodiments, carbon-coated electrodes can be used with high frequency alternating current to further optimize the lifetime of monolith **212**, heating distribution within monolith **212**, and heating efficiency. In some embodiments, a non-impregnated carbon layer is used between electrodes **220** and monolith **212** to provide a chemical barrier between the ions of sorbent **214** and electrodes **220**. In some embodiments, the non-impregnated layer of carbon is activated carbon. In some embodiments, the non-impregnated layer of carbon is not activated carbon. In some embodiments, the carbon layer can include a graphite layer having a thickness of at least about 8 μm. In some embodiments, the carbon layer has a thickness of about 8 μm to about 150 μm (e.g., about 10 μm to about 140 μm, about 20 μm to about 125 μm, about 50 μm to about 100 μm, or about 75 μm to about 100 μm). In some embodiments, the carbon layer has a thickness of about 20 μm to about 150 μm (e.g. about 50 μm to about 125 μm, about 70 μm to about 90 μm). In some embodiments, the carbon layer has a density of about 5 mg/cm^2 to about 10 mg/cm^2, about 6 mg/cm^2 to about 9 mg/cm^2, or about 7 mg/cm^2 to about 8 mg/cm^2. In some embodiments, the carbon layer has a density of about 7.3 mg/cm^2.

[0141] In some embodiments, the carbon layer can include a copper layer. In some embodiments, the copper layer has a thickness of at least 5 μm. In some embodiments, the copper layer has a thickness of about 5 μm to about 150 μm (e.g., about 15 μm to about 140 μm, about 20 μm to about 125 μm, about 50 μm to about 100 μm, or about 75 μm to about 100 μm. In some embodiments, the copper layer has a thickness of about 90 μm. In some embodiments, monolith **212** includes a sorbent **214** that reacts with carbon dioxide to form a carbonate. In some embodiments, the sorbent can be a metal carbonate. In some embodiments, sorbent **214** can be potassium carbonate, calcium carbonate, or a mixture thereof. In some embodiments, sorbent **214** can include an amine. In some embodiments, the amine is monoethylamine, glycine, sarcosine, polyethylenimine, ("PEI"), polyaziridine, linear and/or branched surfactants (e.g., lauric acid), or a mixture thereof.

[0142] In some embodiments, monolith **212** is a solid structure that is impregnated with sorbent **214**. Exemplary monoliths **212** or array **210** of monoliths **212** are illustrated in FIGS. **2**A-**5**. In some embodiments, monolith **212** has a structure that allows fluid **102** to flow through monolith. In some embodiments, monolith **212** is treated or impregnated (e.g., by wet impregnation) with an aqueous solution containing sorbent **214**.

[0143] In some embodiments, the aqueous solution for treating or impregnating monolith **212** can have various amounts of dissolved sorbent **214**. The amount of sorbent **214** in the solution used to impregnate monolith **212** can affect the cumulative amount of carbon dioxide that can be adsorbed by monolith **212**. For example, the solution can contain about 25 wt % to about 75 wt % (e.g., about 40 wt % to about 65 wt %) In some embodiments, the solution contains about 50 wt % of dissolved sorbent **214**. In some embodiments, monolith **212** can adsorb between about 0.4 mmol and about 0.5 mmol of carbon dioxide per gram of sorbent **214**. In some embodiments, monolith **212** is impregnated with a solution containing about 50 wt % sorbent **214**, and monolith **212** can remove between about 0.45 mmol carbon dioxide per gram of sorbent **214**. In some embodiments, monolith **212** can adsorb about 0.44 mmol CO2/g adsorbent in 400 minutes.

[0144] In some embodiments, monolith **212** can include conductive microporous and/or mesoporous activated carbon. In some embodiments, monolith **212** includes microporous activated carbon. In some embodiments, monolith **212** includes mesoporous activated carbon. In some embodiments, monolith **212** can include a hierarchical porous structure where the pores range from mesoporous to microporous.

[0145] In some embodiments, monolith **212** can include one or more binders. In some embodiments, monolith **212** includes binders, such as silicate solution, whey, baking flour, bentonite, natural clays, synthetic clays, or combinations thereof.

[0146] In some embodiments, monolith **212** can include one or more additives. In some embodiments, monolith **212** includes additives, such as graphite, formaldehyde, resorcinol, carbon fiber, carbon nanotubes, carbon nanofibers, nanodiamonds, buckyballs, pure or ligated metal (e.g., copper, aluminum, iron, gold, platinum, palladium, silver), nanoparticles or oxides thereof, zeolites, metal-organic frameworks, covalent organic frameworks, natural or synthetic silicas, polyamine polymers, polyethylene glycol, amino acids, a single or mixture of metal carbonate salts, or combinations thereof.

[0147] FIG. **20** illustrates a flowchart showing a method **2000** for manufacturing a monolith (e.g., monolith **212**). In

some embodiments, at step **2008**, input materials are mixed. As illustrated in FIG. **20**, the input materials can include one or more of activated carbon **2002**, binder **2004**, or additives **2006**. Mixing at step **2008** can be done using various types of mixers, such as a rotary mixer, a planetary mixer, or a centrifugal mixer.

[0148] In some embodiments, at step **2010**, the mixture can be formed into monolith **212**, for example, by extrusion, molding, 3d-printing, or direct polymer synthesis with subsequent carbonization.

[0149] At step **2012**, in some embodiments, monolith **212** is dried to a moisture content of about 0 wt % to about 10 wt %. In some embodiments, monolith **212** is dried to a moisture content of about 2 wt %. At step **2012**, in some embodiments, manufactured monolith **212** is calcined under an inert gas at a temperature of 300° C. to about 900° C. for about 1 hour to about 24 hours. In some embodiments, monolith **212** is calcined at a temperature of about 700° C. In some embodiments, monolith **212** is calcined for about 6 hours. In some embodiments, the inert gas comprises helium, argon, nitrogen, or combinations thereof. In some embodiments, the inert gas has a purity of 99% or more.

[0150] In some embodiments, at step **2014**, dried and calcined monolith **212** is soaked in an aqueous solution of a metal (e.g., a metal carbonate or a Group 1 element salt in the periodic table). In some embodiments, the aqueous solution comprises about 5 wt % to about 50 wt % of the metal. In some embodiments, the aqueous solution comprises about 25 wt % of the metal. In some embodiments, the metal is potassium carbonate. In some embodiments, monolith **212** is soaked in the aqueous solution for about 1 minute to about 24 hours, such as about 10 minutes to about 15 minutes.

[0151] In some embodiments, at step **2016**, excess liquid is removed from soaked monolith **212** by passing a stream of air through each cell in monolith **212** and along the exterior of monolith **212**. In some embodiments, the stream of ambient air (e.g. about −20° C. to about 32° C.) is at a pressure between about 20 psi to about 80 psi (e.g., about 55 psi). In some embodiments, the stream of air is passed through each cell for about 1 minutes to about 60 minutes (e.g., about 10 minutes).

[0152] In some embodiments, at step **2018**, monolith **212** is dried by alternating current joule heating (described below related to method **2100**) and under vacuum with consistent homogenous heating at temperatures between about 25° C. to about 150° C. In some embodiments, at step **2018**, monolith **212** is dried under vacuum without heat application.

[0153] Carbon structures can be prone to cracking during drying. However, methods described related to FIG. **21** can reduce the tendency to crack and increases the consistency of heat distribution in carbon structures when progressive Joule heating is performed. FIG. **21** illustrates a flowchart showing a method **2100** for drying monolith **212** by applying alternating current joule heating.

[0154] At step **2102**, in some embodiments, soaked monolith **212** is placed in an electrical application structure. In some embodiments, the electrical application structure contains a metal plate, a foam, a carbon coated copper electrode, a carbon structure, a carbon coated copper electrode, a foam, and a metal plate. In some embodiments, the electrical application structure contains from inside to outside a metal plate, a foam, a carbon coated copper electrode, a carbon structure, a carbon coated copper electrode, a foam, and a metal plate. In some embodiments, the copper electrodes are placed on opposite sides of the carbon structure at a pressure of at least 5 lbs/in^2.

[0155] At step **2104**, in some embodiments, monolith **212** is heated with alternating current. In some embodiments, the alternating current has a frequency in a range of about 1 Hz to about 100,000 Hz. In some embodiments, the alternating current has a frequency of about 60 Hz. In some embodiments, voltage is controlled, as the resistance of monolith changes with temperature, to maintain the current through monolith less than about 10 amps throughout the heating. In some embodiment, alternating current is applied until monolith **212** reaches 80° C.

[0156] At step **2106**, in some embodiments, after monolith **212** reaches a temperature of about 80° C., remaining steam is removed from monolith **212**. In some embodiments, at step **2106**, hot air (e.g. about 60° C. to about 100° C.) is blown over monolith **212** to remove any steam remaining inside monolith **212**. In some embodiments, the air is blown over monolith **212** until the temperature of monolith **212** is decreased to ambient temperature (e.g. about −20° C. to about 32° C.) by decreasing the temperature of the air to ambient temperature (e.g. about −20° C. to about 32° C.). In some embodiments, the temperature of monolith **212** can be measured by a thermocouple.

[0157] At step **2108**, the flow of air can be stopped. In some embodiments, at step **2108**, the air is blown over monolith **212** until no steam is observed leaving monolith **212**. In some embodiments, at step **2108**, the air is stopped after blowing for about 10 minutes to about 90 minutes.

[0158] In some embodiments, steps **2106** and **2108** are repeated until no steam is observed leaving monolith **212** at the beginning of the hot air flow. In some embodiments, steps **2106** and **2108** are repeated at least 5 times (e.g., at least 6 times). In some embodiments, steps **2106** and **2108** are repeated for about 60 minutes to about 120 minutes (e.g., about 75 minutes to about 90 minutes). In some embodiments, steps **2106** and **2018** are repeated for about 90 minutes. In some embodiments, voltage is increased to maintain the constant current amperage, as the resistance of monolith **212** increases as it dries. In some embodiments, the drying process is stopped when a pre-determined humidity level is reached. In some embodiments, humidity level in the monolith is measured by the weight of the monolith, and the drying process is stopped when about 20% to about 100% of the water weight has been removed.

[0159] At step **2110**, monolith **212** can be cooled. In some embodiments, after drying, at step **2110**, monolith **212** is cooled to room temperature under ambient conditions (e.g. about −20° C. to about 32° C.).

[0160] Method **2100** for drying monolith **212** described above can reduce the tendency for carbon structures to crack during the drying process and increases the consistency of heat distribution in carbon structures when progressive joule heating is performed.

[0161] System **10** can be configured to allow for continuous adsorption of carbon dioxide from fluid source **100**. For example, using the heating methods described herein, monoliths **212** can cycle between a contacting mode (e.g., shown in FIG. **2**A) in which carbon dioxide is adsorbed and a regeneration mode (e.g., shown in FIG. **2**B) in which carbon dioxide is released from the adsorber. In some embodiments,

a first portion of monoliths **212** in array **210** are in contacting mode and a second portion of monoliths **212** in array **210** are in regeneration mode.

[0162] This cycling can be accomplished, for example, by providing a reactor that alternatively seals and unseals monoliths **212**. For example, reactor **200** can have one or more chambers (e.g., chambers **216** and **218**), and each chamber can have one or more monoliths **212** disposed within the chamber. In some embodiments, each chamber is sealed (e.g., by closure **300**) when monoliths disposed therein are in regeneration mode and unsealed when monoliths disposed therein are in contacting mode. In some embodiments, each chamber can be hermetically sealed. In some embodiments, each chamber can be hermetically sealed using vacuum pump (e.g., vacuum pump **700**). In some embodiments, closure **300** can move from a first position that seals a first chamber to a second position that unseals the first chamber. In some embodiments, the second position is a position that seals a second chamber. In some embodiments, closure **300** vacuum seals chambers of reactor **200**.

[0163] In some embodiments, as shown in FIG. **6**, closure **300** can be a pair of doors on opposite sides of reactor **200** that each slide from a first position to a second position. FIG. **6** illustrates a reactor having two chambers, each with one monolith disposed therein. For example, as shown in FIG. **6**, reactor **200** can include first chamber **216** with monolith **212***a* disposed therein and second chamber **218** with monolith **212***b* disposed therein. In the exemplary reactor **200** shown in FIG. **6**, closure **300** is in the first position and first chamber **216** is sealed. In this position, monolith **212***a* is in regeneration mode, meaning system **10** provides electric current **602** to monolith **212***a* to heat monolith **212***a* as described above, which in turn releases carbon dioxide adsorbed by monolith **212***a*. At the same time, monolith **212***b* is in contacting mode, meaning system **10** flows fluid **102** from fluid source **100** through monolith **212***b* such that monolith **212***b* adsorbs carbon dioxide and fluid **104** (e.g., fluid **102** less carbon dioxide) flows out of reactor **200**. Once system **10** detects that a certain condition has been met, for example based on time elapsed, saturation level of monolith **212***b*, or amount of carbon dioxide being released from monolith **212***a*, closure **300** or **320** may move to a second position in which second chamber **218** is sealed and first chamber **216** is unsealed. In this portion of the cycle, the operation is reversed from what is described above, for example, monolith **212***a* is in contacting mode and monolith **212***b* is in regeneration mode. In some embodiments, closure **300** can slide within tracks **206** to unseal first chamber **216** and move to a second position in which second chamber **218** is sealed.

[0164] FIG. **7** shows another exemplary arrangement of reactor **200** that follows the same contacting and regeneration cycling as the reactor shown in FIG. **6**. For example, FIG. **7** shows exemplary reactor **200** with a first chamber **216** containing a first 12×6 array **210** of monoliths **212** disposed within a first chamber and a second 12×6 array of monoliths **212** disposed within a second chamber (shown sealed behind closure **300** in FIG. **7**). Closure **300** shown in FIG. **7** includes a pair of sliding doors that can each slide between a first position and a second position as described above related to FIG. **6**. In some embodiments, each door of closure **300** is disposed on opposite sides of the reactor. In some embodiments, when first chamber **216** or second chamber **218** is unsealed, all monoliths **212** disposed therein are in contacting mode. In some embodiments, when first chamber **216** or second chamber **218** is sealed, all monoliths **212** disposed therein are in regeneration mode.

[0165] FIG. **8** shows an exemplary arrangement of reactor **200** that includes a 10×11 array of monoliths. In some embodiments, as shown in FIG. **8**, closure **300** is a box that moves from a first position (shown in FIG. **8**) to a second position to seal array **210**. In some embodiments, closure **300** slides along tracks **312** on frame **310** to a second position in which a contacting end **314** of closure **300** contacts sealing surface **308**. In some embodiments, when closure **300** is in the first position (shown in FIG. **8**), monoliths **212** are in the contacting mode. In some embodiments, when closure **300** is in the second position, monoliths **212** are in the regeneration position.

[0166] FIGS. **22** and **23** show exemplary arrangement of reactor **200** having one or more monoliths **212** disposed within housing **302** and frame **332**. In some embodiments, reactor **200** includes one or more closures **320**. In some embodiments, reactor **200** includes two closure **320**. In some embodiments, a first closure **320** is disposed on a first side of frame **332** and a second closure **320** is disposed on a second side of frame **332** opposite the first side, as shown in FIG. **23**. In some embodiments, when both closures are open, a fluid (e.g., fluid **102**) can flow across monoliths **212** and reactor **200** can be in contacting mode. In some embodiments, when both closures are closed, a fluid cannot pass across monoliths **212** and reactor **200** can be in regeneration mode.

[0167] In some embodiments, closure **320** is hingedly coupled to reactor **200**. In some embodiments, closure **320** is coupled to frame **332** by at least one hinge **322**. In some embodiments, closure **320** is coupled to frame **332** by two hinges **322**.

[0168] In some embodiments, closure **320** can be opened and closed using one or more hydraulic cylinders **324**. In some embodiments, hydraulic cylinder **324** includes cylinder **326** and rod **328**. Hydraulic cylinder **324** can actuate between a retracted position and an extended position. FIG. **22** illustrates hydraulic cylinder **324** in the extended position. In some embodiments, hydraulic cylinder **324** moves closure **320** from an open position (shown in FIG. **22**) to a closed position. In some embodiments, in the closed position, closure **320** engages with clamps **330** on frame **332**. In some embodiments, clamp **330** can be a pneumatic or hydraulic clamp. In some embodiments, clamp **330** engages with closure **320** to secure closure **320** in the closed position. In some embodiments, in the closed position, closure **320** couples to sealing surface **308** to seal reactor **200**. In some embodiments, in the closed position, closure **320** is sealed under vacuum. In some embodiments, when hydraulic cylinder **324** extends, closure **320** is in the first position (shown in FIG. **22**), monoliths **212** are in the contacting mode. In some embodiments, when hydraulic cylinder **324** contracts, closure **320** is in the closed position, and monoliths **212** are in the regeneration mode. In some embodiments, when hydraulic cylinder **324** extends, closure **320** is in the open position, and monoliths **212** are in the contacting mode. In some embodiments, reactor **200** can include two closures **320** on opposite sides of reactor **200**. In some embodiments, reactor **200** is in contacting mode when both closures **320**

are in the open position. In some embodiments, reactor **200** is in the regeneration mode when both closures **320** are in the closed position.

[0169] In some embodiments, closure **320** is flexible, which can allow closure **320** to be light and reduce material costs. In some embodiments, closure **320** can be used for about 25,000 cycles to about 500,000 cycles, about 35,000 cycles to about 400,000 cycles, about 45,000 cycles to about 250,000 cycles, about 75,000 cycles to about 150,000 cycles, or within a range having any two of these values as endpoints. In some embodiments, in the context of closure **320**, one cycle includes opening closure **320** and closing closure **320**.

[0170] In some embodiments, as shown in FIG. **22**, reactor **200** can be coupled to duct **334**. In some embodiments, duct **334** includes fan **400** that can be used to draw fluid (e.g., fluid **102**) through monoliths **212**. In some embodiments, multiple reactors **200** can be coupled to the same duct. For example, as shown in FIG. **24**, multiple reactors **200** can be stacked or placed side-by-side. FIG. **23** illustrates the reactor **200** of FIG. **22** that is not coupled to duct **334**. an exemplary arrangement of reactor **200** that has a similar hinged closure **320** as reactor **200** shown in FIG. **22**.

[0171] Closures **300** and **320** can move between a first position and a second position. In some embodiments, closure **300** is slidably coupled to a reactor (e.g., reactor **200**) and slides between the first position and the second position. In some embodiments, closure **320** is hingedly coupled to a reactor (e.g., reactor **200**) and rotate between the first position and the second position. In some embodiments, closure **320** is open in the first position and closed in the second position.

[0172] In some embodiments, closure **300** and closure **320** can move between the first position and the second position based on various factors, such as time elapsed in one position, amount of fluid **102** entering reactor **200**, concentration of carbon dioxide in fluid **102**, carbon dioxide concentration in product stream **103**, or amount of carbon dioxide exiting reactor **200** through product stream **105**. In some embodiments, system **10** includes solenoid **107** in line with product stream **105**.

[0173] In some embodiments, closures **300** and **320** can move between the first position and the second position after closures **300** and/or **320** have been in one position for a predetermined time has elapsed. In some embodiments, the predetermined time is about 10 minutes to about 120 minutes (e.g., about 10 minutes to about 90 minutes, about 20 minutes to about 70 minutes, or about 20 minutes to about 60 minutes). In some embodiments, closures **300** and/or **320** move from a first position to a second position after a predetermined time has elapsed and then moves back to the first position after the predetermined time has elapsed again.

[0174] In some embodiments, system **10** includes one or more sensors for measuring concentration of carbon dioxide in fluid **102** and volumetric flow rate of fluid **102**. In some embodiments, system **10** includes a first sensor on inlet stream **101** that measures the concentration of carbon dioxide in fluid **102**. In some embodiments, system **10** includes a second sensor on inlet stream **101** to reactor **200** that measures the flow rate of fluid **102** entering reactor **200**. In some embodiments, system **10** includes a single sensor on inlet stream **101** that measures both concentration of carbon dioxide in fluid **102** and the flow rate of fluid **102** entering reactor **200**. In some embodiments, closures **300** and/or **320** can move between the first position and the second position based on one or more signals received from first sensor and/or second sensor. For example, in some embodiments, if system **10** determines, based on the one or more sensors, that a predetermined amount of carbon dioxide has entered reactor **200**, closures **300** and/or **320** can move between the first position and the second position. In some embodiments, the predetermined amount of carbon is about 0.15 mmol to about 1.5 mmol (e.g., about 0.25 mmol to about 1 mmol or about 0.25 mmol to about 0.5 mmol) carbon dioxide per gram of monolith disposed in each chamber.

[0175] In some embodiments, system **10** includes one or more sensors disposed downstream of an outlet to reactor **200** that measures the concentration of carbon dioxide in fluid **104** at product stream **103**. In some embodiments, a concentration of carbon dioxide in product stream **103** that exceeds a predetermined value can indicate that a monolith disposed within the chamber is saturated with carbon dioxide during the contacting mode. In some embodiments, if system **10** determines, based on the one or more sensors, that a concentration of carbon dioxide in product stream **103** exceeds a predetermined value, closures **300** and/or **320** can move between the first position and the second position. In some embodiments, the predetermined concentration value is about 80 wt % to 95 wt % (e.g., about 85 wt % to about 90 wt %).

[0176] In some embodiments, system **10** includes one or more sensors disposed downstream of an outlet to reactor **200** that measures the flow rate of carbon dioxide-rich stream **106** in product stream **105**. In some embodiments, a flow rate of carbon dioxide-rich stream **106** that is less than a predetermined value can indicate that all or substantially all of the carbon dioxide adsorbed by monolith **212** has been released during regeneration mode. In some embodiments, if system **10** determines, based on the one or more sensors, that the flow rate of carbon dioxide-rich stream **106** is less than a predetermined value, closure **300** and/or **320** can move between the first position and the second position. In some embodiments, the predetermined flow rate value is about 10 volume % to about 0.1 volume % (e.g., about 7.5 volume % to about 2.5 volume %). In some embodiments, one or more of the sensors described above are part of carbon dioxide analyzer **502**.

[0177] FIG. **25** illustrates an exemplary schematic of system **10** according to some embodiments. In some embodiments, system **10** includes reactor **200**, fan **400**, pressure controller **500**, power source **600**, and vacuum pump **700**. System **10** can include a control system that includes controller **500**, carbon dioxide analyzer **502**, temperature sensor **504**, velocity sensors **506**, timer **508**, pressure sensors **510**, valves **512**, separator **514**, and flow meter **518**.

[0178] In some embodiments, fan **400** draws fluid through reactor **200** during contacting process. In some embodiments, vacuum pump **700** starts to vacuum reactor **200** after closure **300** and/or **320** is sealed. In some embodiments, pressure sensor **510** measures the pressure within the sealed chamber of reactor **200**. In some embodiments, the output from pressure sensor **510** indicates whether the sealed chamber of reactor **200** has reached a vacuum condition and is used to determine when the regeneration process can begin. In some embodiments, pressure sensor **510** is a transducer coupled to reactor **200**.

[0179] In some embodiments, when the regeneration process begins, power source **600** supplies power to reactor **200**

(or modular unit **250**). In some embodiments, temperature sensor **504** measures the temperature within the sealed chamber of reactor **200**, and the output from temperature sensor **504** is used to determine the duration of power-on and power-off of power source **600**. In some embodiments, temperature sensor **504** is an NTC thermistor. For example, in some embodiments, when temperature sensor **504** detects the temperature within the sealed chamber falls below a minimum temperature, power source **600** is turned on, and when temperature sensor **504** detects the temperature within the sealed chamber exceeds a maximum temperature, power source **600** is turned off. In some embodiments, the minimum temperature is about 80° C. and the maximum temperature is about 200° C. In some embodiments, temperature sensor **504** measures the temperature continuously during the regeneration process.

[0180] In some embodiments, during the regeneration process, second product stream **105** is fed through water separator **514** to separate water from carbon dioxide-rich stream **106** released from reactor **200**. In some embodiments, flow meter **518** measures the flowrate of carbon dioxide-rich stream **106**, and the output of flow meter **518** is used to determine when power source **600** can be turned off. In some embodiments, carbon dioxide analyzer **502** measures the carbon dioxide concentration of carbon dioxide-rich stream **106**, and the output of carbon dioxide analyzer **502** is used to determine when power source **600** can be turned off.

[0181] In some embodiments, solenoid valves **512** gate the chamber of reactor **200** to fan **400** and vacuum pump **700**. In some embodiments, solenoid valves **512** controls the sealing and venting of the chamber of reactor **200**. In some embodiments, solenoid valves **512** are controlled by controller **500**.

[0182] In some embodiments, monoliths **212** disclosed herein have a life of about 1 month to about 1 year. In some embodiments, monolith **212** disclosed herein can have a life of about 100 cycles to about 5000 cycles (e.g., about 500 cycles to about 3000 cycles or about 1000 cycles to about 2000 cycles). In some embodiments, one cycle is one occurrence of the contacting mode and one occurrence of the regeneration model. In some embodiments, a cycle may begin with either the contacting mode or the regeneration mode.

[0183] FIGS. **9** and **10** show exemplary reactors (reactor **200**) integrated with cooling towers according to some embodiments. Cooling towers (e.g., cooling tower **800**) draw hot air out of systems, such as refrigeration systems, HVAC systems, or industrial processes. Hot air enters cooling tower **800** at an inlet. In some embodiments, reactor **200** can be integrated into a cooling tower at the inlet of the cooling tower such that fluid **102** (e.g., ambient air) is drawn through reactor **200** before entering cooling tower **800**. As such, integrating reactor **200** with cooling tower **800** efficiently uses the fluid flow created by cooling tower **800**, which can reduce the power required by system **10**. Additionally, flowing fluid **102** through reactor **200** does not have a significant effect on the performance of cooling tower **800**.

[0184] In some embodiments, as shown in FIG. **9**, cooling tower **800** can be a one-sided inlet cooling tower. In some embodiments, as shown in FIG. **10**, cooling tower **800** can be a two-sided cooling tower (e.g., a cooling tower with more than one inlet) with two or more inlets and a reactor **200** at each inlet. In some embodiments, cooling tower **800** includes more than one inlet and reactor **200** is attached to every inlet of cooling tower **800**. In some embodiments, reactor **200** is a modular design with multiple chambers connected together, such that it can be used with cooling towers of different shapes and scales.

[0185] In some embodiments, extracted carbon dioxide exits reactor **200** as carbon-dioxide rich stream **106** and does not enter cooling tower **800**. In some embodiments, fluid **104** (e.g., fluid **102** less carbon dioxide) exits reactor **200** and enters cooling tower **800** to act as cooling media. In some embodiments, the pressure drop across reactor **200** is small enough that it does not impact operation of the cooling tower. In some embodiments, the pressure drop is in a range of 0.2 inches of water column to 1.1 inches of water column, 0.4 inches of water column to 0.7 inches of water column, or 0.5 inches of water column. In some embodiments, the cooling performance of fluid less carbon dioxide **104** is reduced less than 5% comparing to the cooling performance of fluid **102**, if it does not pass through reactor **200**.

[0186] In some embodiments, reactor **200** is not attached to cooling tower **800** but instead draws fluid **102** directly from the environment. In some embodiments, reactor **200** is a modular unit that can be assembled into a modular system **20**. Modular system **20** can include two or more modular units **250**. In some embodiments, modular units **250** can be stacked vertically, disposed horizontally, or arranged in an array (e.g., as shown in FIG. **24**). In some embodiments, each modular unit **250** includes all components of reactor **200** described. In some embodiments, modular unit **250** includes a reactor **200** with a closure **300** that slides (e.g., as illustrated in FIG. **6**). In some embodiments, modular unit **250** includes a reactor **200** with a closure **320** that is hingedly coupled to reactor **250** (e.g., as illustrated in FIG. **22**). In some embodiments, modular system **20** can include some modular units **250** with closures **300** and some modular units **250** with closures **320**.

[0187] Modular system **20** can include 2 or more modular units **250**. In some embodiments, modular system **20** can include from 2 to 600,000 modular units **250**. In some embodiments, the number of modular units **250** in modular system **20** is in a range from about 100 to about 550,000, from about 1000 to about 500,000, from about 5000 to about 450,000, from about 10,000 to about 400,000, from about 50,000 to about 300,000, from about 100,000 to about 200,000, or within a range having any two of these values as endpoints. In some embodiments, modular units **250** are arranged in an array having dimensions m xn (i.e., m columns of modular units **250** and n rows of modular units **250**), where m is an integer from 1 to 1000 and n is an integer from 1 to 1000. FIG. **24** illustrates a modular system **20** with 24 modular units **250**. As shown in FIG. **24**, m=4 and n=6. The number of modular units **250** can be determined based on the needs of a specific site. A benefit to the modular units **250** is that a modular system **20** can be scaled up or down as needed. In some embodiments, each modular unit **250** is removably coupled to the modular system **20** and/or to another modular unit **250**. For example, a first modular unit **250** can be removably coupled to a second modular unit **250**. In some embodiments, each modular unit **250** is removably coupled to a frame configured to accommodate numerous modular unit **250**. In some embodiments, modular units **250** can be coupled to the system (e.g., system **20**) using fasteners (e.g., screws and nuts). Modular units can be replaced by disconnecting components such as piping

and instrumentation connections, removing fasteners, and lifting out of the cluster of modules.

[0188] In some embodiments, each modular unit **250** is coupled to a duct (e.g., duct **334**) through which air flows after passing over monolith **212**. In some embodiments, each modular unit **250** is coupled to a separate duct. In some embodiments, more than one modular unit **250** is coupled to the same duct. In some embodiments, all modular units **250** within modular system **20** are coupled to the same duct. In some embodiments, duct **334** includes a fan (e.g., fan **400**) that draws air from the environment, through each modular unit **250**, and into duct **334**.

[0189] Modular system **20** can take various forms. For example, as shown in FIGS. **26** and **27**, modular system **20** can include tower **402** with walls **404** of modular units **250**. As shown in FIG. **26**, each wall **404** can include 2 or more (e.g., 3 or more, 4 or more, 5 or more, 6 or more, 7 or more, 8 or more, 9 or more, or 10 or more) modular units **250**. In some embodiments, as shown in FIGS. **26** and **27**, six walls **404** of modular units **250** can be arranged to form a hexagonal shape when viewed top-down. It is to be understood that different numbers of walls **404** could be used to form differently shaped towers **402**. In some embodiments, the number of walls **404** is equal to the number of sides of tower **402**. For example, three walls **404** can be arranged to form a triangular shape when viewed top-down; four walls **404** can be arranged to form a quadrilateral (e.g., a square or a rectangle) when viewed top-down; five walls **404** can be arranged to form a pentagon when viewed top-down; seven walls **404** can be arranged to form a heptagon; or **8** walls can be arranged to form an octagon. In some embodiments, tower **402** includes n walls **404** arranged to form a shape having n sides when tower **402** is viewed top-down, where n is an integer from 4 to 100. Modular units **250** are assembled into reactor towers **402**.

[0190] In some embodiments, outer sides of walls **404** define outer sides of tower **402**. In some embodiments, inner sides of walls **404** define a duct (e.g., duct **334**). In some embodiments, reactor tower **402** includes fan **400** to draw fluid through each of modular units **250** and into duct **334**. In some embodiments, reactor tower **402** includes a single fan **402**. In some embodiments, reactor tower **402** includes multiple fans (e.g., 2 or more fans, 3 or more fans, 5 or more fans, or 10 or more fans).

[0191] In some embodiments, tower **402** sits on a substrate (e.g., on the ground, on a concrete pad, or on a rooftop). In some embodiments, tower **402** is elevated above the substrate. In some embodiments, reactor tower **402** includes supports **412** to elevate reactor tower **402**. In some embodiments, supports **412** stabilize reactor tower **402**. Systems disclosed herein can have any number of reactor towers **402**, depending on the site and conditions of the environment. In some embodiments, systems disclosed herein can include 1 or more reactor towers **402** (e.g., 2 or more reactor towers, 3 or more reactor towers, 5 or more reactor towers, 10 or more reactor towers). In some embodiments, system **20** includes two reactor towers **402**, as shown in FIG. **26**.

[0192] In some embodiments, system **20** includes electrical and control unit **406** coupled to reactor tower **402**. In some embodiments, site **20** includes carbon dioxide purification unit **408** connected to reactor tower.

[0193] In some embodiments, modular units **250** can be manufactured from sheet metal. In some embodiments, modular units **250** can be manufactured from sheet metal have a size of, for example, 4 ft×10 ft or 4 ft×8 ft. In some embodiments, modular units **250** are sized to increase shipping efficiency. In some embodiments, each modular unit **250** can be transported by standard shipping means (e.g., a semi-trailer, train, shipping container, etc.).

[0194] Systems (e.g., system **10**) disclosed herein include various electrical systems to operate, monitor, and adjust the systems. Electrical systems can include, for example, power sources that provide electricity to the systems; electrical conduits (e.g., electrodes **220**) for supplying electricity to monoliths for heating; and sensors for monitoring temperature of the monoliths, saturation level of monoliths, fluid composition of fluid entering system **10**, and amount of carbon dioxide exiting system **10**.

[0195] In some embodiments, one or more electrodes (e.g., electrodes **220**) are coupled to monolith **212**. In some embodiments, electrodes **220** are electrically coupled to a source of electricity (e.g., power source **600**). In some embodiments, as shown in FIG. **5**, four electrodes may be used on four different sides of monolith **212**. In some embodiments, as shown in FIG. **5**, system **10** can include switch **604** that switches current from one electrode **220** on a first side of monolith **212** to another electrode **220** that is coupled to a second side of monolith **212** that is perpendicular to the second side. In some embodiments, when switch **604** switches between electrodes **220** as shown in FIG. **5**, electric current **602** can pass through monolith **212** in an alternating fashion between horizontal and vertical. This configuration increases homogeneity of temperature within monolith **212** as it is headed.

[0196] FIG. **13** illustrates an electrical system of system **10** according to some embodiments. In some embodiments, system **10** can include 1 or more (e.g., 2 or more, 3 or more, 4 or more, or 5 or more) power sources **600**. In some embodiments, as shown in FIG. **13**, system **10** can include one power source per array **210** of monoliths **212**. In some embodiments, the ratio of the number of power sources **600** to the number of monoliths **212** is 1:100 to about 1:1 (e.g., about 1:50 to about 1:5 or about 1:30 to about 1:10). As discussed above, chambers containing monoliths can be hermetically sealed. FIG. **13** illustrates feedthrough lines **606** that can be used to pass electric current **602** and sensor signals in and out of sealed chambers. in this configuration there are multiple monoliths sharing electric leads. This allows for power of multiple. In some embodiments, as shown in FIGS. **3** and **28**, multiple series of monoliths **212** can be arranged in parallel, with electrodes **220** disposed between each series of monoliths **212**. In some embodiments, in the parallel arrangement, the power distribution is low voltage and high current. In some embodiments, as shown in FIGS. **3** and **28**, electrical leads can be physically connected to power multiple columns at the same time. In some embodiments, as shown in FIG. **29**, power is distributed to monoliths **212** in series. In some embodiments, in the series arrangement, the power distribution is high voltage and low current.

[0197] In some embodiments, each power source (e.g., power source **600**) is configured to provide a consistent direct current voltage to monoliths **212** or arrays **210** of monoliths **212**. In some embodiments, power source **600** provides a direct current (e.g., electric current **602**) having a voltage of about 12 volts to about 90 volts (e.g., about 30 volts to about 80 volts or about 50 volts to about 70 volts). In some embodiments, power source **600** provides a direct

current having a voltage of about 50 volts. As discussed above, electrodes **220** can be adhered to monolith **212**. In some embodiments, the adhesive is selected such that that the connection between the monolith and the electrode is less resistive per unit length than the monolith itself. This ensures that joule heating is the main source of heat.

[0198] In some embodiments, regeneration of carbon dioxide in monoliths (e.g., monoliths **212**) is driven by heating monoliths with direct ohmic heating also known as joule heating. In some embodiments, monoliths **212** are arranged as loads in a series-parallel arrangement in order to maximize power supply efficiency and efficacy. In some embodiments, each power source (e.g., power source **600**) is transformed from 3-phase grid alternate current mains to direct current, and then inverted back into single phase alternate current. Through power switches, each single phase alternate current is connected to a series of monoliths **212** either in parallel connection (FIG. **29**) or series connection (FIG. **28**). In some embodiments, each output is connected to a series-parallel string of monoliths, and each string of monoliths is filled with monoliths of similar DC resistance. In some embodiments, the 3-phase power includes a variable DC rail, an AC inverter, and a control unit. In some embodiments, the variable DC rail operates at 20 Volts direct current ("VDC") to 105 VDC and can produce greater than 12 kW at 105 VDC. In some embodiments, the AC inverter operates at a frequency of 100 kHz and can produce 12 kW. In some embodiments, the series-parallel string of monoliths can includes 2 or more (e.g., 4 or more, 6 or more, 8 or more, or 10 or more) rows of monoliths **212**, and the monoliths **212** can be arranged in series. Each row can be arranged parallel to the next.

[0199] One factor that affects the efficiency of the system is the resistance of the monoliths used in the system. In some embodiments, the resistance of the monoliths is designed to ensure relatively even heating throughout the array **210** of monoliths **212**. If the circuit is designed such that the monoliths are in parallel, as illustrated in FIG. **14**A, the voltage across each monolith will be constant, but the current and, therefore, the heating power will vary inversely with the resistance of each monolith. For example, in a two-monolith system with monoliths (represented by **R1** and **R2**) in parallel, as shown in FIG. **14**A, if a constant direct current voltage is applied across the monoliths, monolith **R2** will have a resistance 2 times that of **R1**, meaning the heating power applied to **R1** will be 2 times that of **R2**. If the circuit is designed such that the monoliths are set in series, as shown in FIG. **14**B, the opposite will occur. For example, the current across both monoliths will be constant, but the voltage across **R2** will be twice the voltage across **R1**, and therefore the heating power through **R2** will be twice that across **R1**.

[0200] Equation 1 below shows the relationship between heat (Q), mass (m), specific heat capacity (c_p), and temperature (T). Based on Equation 1 below, two monoliths with the same masses and specific heat capacities that are being heated will increase in temperature in direct relation to the amount of heating energy (e.g., electrical energy provided by electric current **602**) moving through each of the monoliths.

$$Q = m c_p \Delta T \quad \text{Eq. 1}$$

[0201] As described above, the heating energy is impacted by the electrical resistance of each monolith. In some embodiments, the resistances across impregnated monoliths according to some embodiments (e.g., monoliths **212**) varies in the range of 5 ohms to 5,000,000 ohms. Accordingly, systems disclosed herein may be designed for resistance balancing. In some embodiments, the resistance range for monoliths being powered by a single power supply will is in a range of +20% of the target range. In some embodiments, monoliths in parallel have a resistance range of +100 ohms of the target range.

[0202] In some embodiments, resistivity for a monolith having dimensions of 4 inches cubed with 100 cells per square inch will be about 2.0 Ohm to about 40.0 Ohms, including the resistivity of any adhesive used to connect electrodes to the monolith. In some embodiments, the resistivity is measured perpendicular to the flow of fluid (e.g., fluid **102**). In some embodiments, the resistivity of monolith **212** is directly related to the width of monolith **212** as measured from one electrode surface to the other electrode surface on the opposite side. In some embodiments, the resistivity of monolith **212** also changes according to the water concentration or carbon dioxide amount of monolith **212**.

[0203] As discussed above, systems disclosed herein offer benefits of carbon dioxide capture and rapid regeneration in an energy efficient manner. In some embodiments, system **10** uses about 10 Joules to about 200 Joules per monolith per regeneration cycle.

[0204] In some embodiments, when system **10** is integrated with a cooling tower (e.g., cooling tower **800**), system **10** can remove between about 10 kg and about 10 tons of carbon dioxide per day (e.g., about 500 kg to about 3 tons of carbon dioxide per day). In some embodiments, system **10** can remove about 20% to about 85% (e.g., about 40% to about 70%) of carbon dioxide from fluid **102**.

[0205] In some embodiments, system **10** can be integrated into a system that includes reactor **200**, cooling tower **800**, and a sequestration system that permanently removes the carbon dioxide from the atmosphere.

[0206] FIG. **15** shows method **1000** of operating reactor **200** according to some embodiments. In some embodiments, at step **1010** fluid **102** flows through monolith **212** disposed in first chamber **216**. In some embodiments, at step **1020**, fluid **102** contacts monolith **212** such that carbon dioxide in fluid **102** is adsorbed by monolith **212**. In some embodiments, at step **1030** system **10** determines whether monolith **212** is saturated with carbon dioxide to a predetermined value. In some embodiments, the predetermined saturation value is in a range of 50% to 100% (e.g., 60% to 100%, 75% to 100%, or 90% to 100%). In some embodiments, the saturation value can be determined by the weight of monolith **212**. In some embodiments, the saturation value can be determined by monitoring the carbon dioxide concentration of fluid **102** that enters reactor **200** and the carbon dioxide concentration of fluid **104** that exists reactor **200**.

[0207] In some embodiments, if monolith **212** is not saturated to the predetermined value, system continues steps **1010**, **1020**, and **1030** until system **10** determines that monolith **212** is saturated. In some embodiments, if monolith **212** is saturated to the predetermined value, system **10** moves to step **1040** and seals first chamber **216**. In some embodiments, as discussed in detail above, the sealing first chamber **216** is done by sliding closure **300** to engage with

sealing surface **308**. In some embodiments, at step **1040**, first chamber **216** is hermetically sealed. In some embodiments, first chamber **216** is sealed by vacuum pump **700**. In some embodiments, at step **1050** electric current (e.g., electric current **602**) is applied to monolith **212** to release adsorbed carbon dioxide. In some embodiments, the electric current is applies through electrode **220** attached to a surface of monolith **212**. In some embodiments, at step **1060** the released carbon dioxide is collected downstream of reactor **200**. In some embodiments, at step **1060**, the collected carbon dioxide is released from system **10**, for example through carbon dioxide-rich stream **106**.

[0208] In some embodiments, at step **1070** carbon dioxide-rich stream **106** is analyzed (e.g., by analyzer **502**) to determine the amount of carbon dioxide in carbon dioxide-rich stream **106**. In some embodiments, if the carbon dioxide amount in carbon dioxide-rich stream **106** is not less than the predetermined value, in some embodiments, method **1000** repeats steps **1050**, **1060**, and **1070**. In some embodiments, if the carbon dioxide amount in carbon dioxide-rich stream **106** is less than the predetermined value, this can indicate that all or substantially all of the adsorbed carbon dioxide has been released, and at step **1080**, system **10** stops applying electric current **602** to monolith **212** and unseals first chamber **216**. Although method **1000** is described with respect to first chamber **216**, it is to be understood that method **1000** can also be performed using second chamber **218**. In some embodiments, method **1000** is performed with monolith **212** disposed in second chamber **218** occurs in parallel, simultaneously, or alternating with method **1000** applied to monolith **212** disposed in first chamber **216**. For example, in some embodiments, when steps **1010**, **1020**, and **1030** are applied to monolith **212** disposed in first chamber **216**, steps **1050**, **1060**, and **1070** are applied to monolith **212** disposed in second chamber **218**.

[0209] FIG. **16** shows a method **1100** of operating reactor **200** according to some embodiments. In some embodiments, steps **1110** and **1120** are the same as steps **1010** and **1020** in method **1000**. In some embodiments, at step **1130**, the system determines if a first predetermined time has been reached. In some embodiments, if the predetermined time has been reached, method **1100** repeats steps **1110**, **1120**, and **1130** until the predetermined time has been reached. In some embodiments, if at step **1130** the system determines that a predetermined time has been reached, method **1100** proceeds to steps **1140**, **1150**, **1160**, which are the same as steps **1040**, **1050**, **1060**, respectively. In some embodiments, the first time is in a range of about 20 minutes to about 70 minutes (e.g., about 30 minutes to about 60 minutes or about 40 minutes to about 50 minutes).

[0210] In some embodiments, if the first time is not reached, method **1100** repeats steps **1110**, **1120**, and **1130** until the first time has been reached. In some embodiments, at step **1170**, the system determines if a second predetermined time has been reached. In some embodiments, if the second predetermined time has not been reached, the system repeats steps **1150** and **1160**. In some embodiments, if the second predetermined time has been reached, system **10** stops applying electric current **602** to monolith **212** and unseals first chamber **216**. Although method **1100** is described with respect to first chamber **216**, it is to be understood that method **1100** can also be performed using second chamber **218**. In some embodiments, method **1100** is performed with monolith **212** disposed in second chamber **218** occurs in parallel, simultaneously, or alternating with method **1100** applied to monolith **212** disposed in first chamber **216**. For example, in some embodiments, when steps **1110**, **1120**, and **1130** are applied to monolith **212** disposed in first chamber **216**, steps **1150**, **1160**, and **1170** are applied to monolith **212** disposed in second chamber **218**.

[0211] As used herein, the terms "left" and "right," and "top" and "bottom," and the like are intended to assist in understanding of embodiments of the disclosure with reference to the accompanying drawings with respect to the orientation of monoliths, electrodes, etc. as shown, and are not intended to be limiting to the scope of the disclosure or to limit the disclosure scope to the embodiments depicted in the Figures. The directional terms are used for convenience of description and it is understood that may be positioned in any of various orientations.

[0212] As used herein, when the term "about" is used in describing a value or an end-point of a range, the disclosure should be understood to include the specific value or end-point referred to. As used herein, the term "about" may include ±10%.

[0213] It is to be appreciated that the Detailed Description section, and not any other section, is intended to be used to interpret the claims. Other sections may set forth one or more but not all exemplary embodiments of the present disclosure as contemplated by the inventor(s), and thus, are not intended to limit the present disclosure and the appended claims in any way.

[0214] The present disclosure has been described above with the aid of functional building blocks illustrating the implementation of specified functions and relationships thereof. The boundaries of these functional building blocks have been arbitrarily defined herein for the convenience of the description. Alternate boundaries can be defined so long as the specified functions and relationships thereof are appropriately performed.

[0215] The foregoing description of the specific embodiments will so fully reveal the general nature of the disclosure that others can, by applying knowledge within the skill of the art, readily modify and/or adapt for various applications such specific embodiments, without undue experimentation, without departing from the general concept of the present disclosure. Therefore, such adaptations and modifications are intended to be within the meaning and range of equivalents of the disclosed embodiments, based on the teaching and guidance presented herein. It is to be understood that the phraseology or terminology herein is for the purpose of description and not of limitation, such that the terminology or phraseology of the present specification is to be interpreted by the skilled artisan in light of the teachings and guidance.

[0216] The above examples are illustrative, but not limiting, of the present disclosure. Other suitable modifications and adaptations of the variety of conditions and parameters normally encountered in the field, and which would be apparent to those skilled in the art, are within the spirit and scope of the disclosure.

[0217] References in the specification to "one embodiment," "an embodiment," "an example embodiment," "some embodiments," etc., indicate that the embodiment described may include a particular feature, structure, or characteristic, but every embodiment may not necessarily include the particular feature, structure, or characteristic. Moreover,

such phrases are not necessarily referring to the same embodiment. Further, when a particular feature, structure, or characteristic is described in connection with an embodiment, it is submitted that it is within the knowledge of one skilled in the art to affect such feature, structure, or characteristic in connection with other embodiments whether or not explicitly described.

[0218] The breadth and scope of the present disclosure should not be limited by any of the above-described exemplary embodiments, but should be defined only in accordance with the claims and their equivalents.

1. A system for extracting carbon dioxide from a fluid, the system comprising:
- a fluid source; and
- a reactor comprising:
  - an inlet configured to receive the fluid from the fluid source;
  - an outlet configured to remove the fluid from the reactor;
  - a first chamber in fluid communication with the inlet and the outlet, wherein the first chamber comprises a first monolith, and wherein the first monolith comprises a first sorbent configured to adsorb carbon dioxide;
  - a second chamber in fluid communication with the inlet and the outlet, wherein the second chamber comprises a second monolith, and wherein the second monolith comprises a second sorbent configured to adsorb carbon dioxide;
  - an electric conduit configured to provide an electric current to the first monolith and the second monolith to release carbon dioxide adsorbed by the first monolith and the second monolith; and
  - a closure configured to move between a first position and a second position, wherein the closure is configured to seal the first chamber in the first position and seal the second chamber in the second position.

2. The system of claim **1**, wherein the electric conduit is configured to provide the electric current to the first monolith when the closure is in the first position and provide the electric current to the second monolith when the closure is in the second position.

3. The system of claim **1**, wherein the electric conduit comprises a first electrode coupled to a surface of the first monolith and a second electrode coupled to a surface of the second monolith, and wherein the electric conduit is configured to provide the electric current to the first monolith and second monolith through the first electrode and the second electrode.

4. (canceled)

5. The system of claim **1**, wherein the electric conduit is configured to provide the electric current to heat the first monolith and second monolith to a temperature in a range of 80° C. to 200° C.

6. The system of claim **5**, wherein the electric conduit is configured to provide the electric current to heat the first monolith and second monolith to a temperature in a range of 120° C. to 180° C.

7-10. (canceled)

11. The system of claim **1**, further comprising a collector, wherein the collector is configured to collect carbon dioxide that is released from the first sorbent and the second sorbent.

12. The system of claim **1**, wherein each of the first sorbent and the second sorbent comprises a metal carbonate.

13. The system of claim **12**, wherein the metal carbonate comprises at least one of potassium carbonate or calcium carbonate.

14. (canceled)

15. The system of claim **1**, wherein a difference between the pressure of the fluid at the inlet and the pressure of the fluid at the outlet is in a range of 0.2 inches of water column to 1.1 inches of water column.

16. The system of claim **1**, further comprising a fan configured to direct the fluid from the fluid source to the inlet.

17-18. (canceled)

19. The system of claim **1**, wherein the fluid is ambient air.

20-21. (canceled)

22. The system of claim **1**, wherein the reactor further comprises a first carbon dioxide outlet in fluid communication with the first chamber, the first carbon dioxide outlet configured to remove carbon dioxide released from the first monolith, and a second carbon dioxide outlet in fluid communication with the second chamber, the second carbon dioxide outlet configured to remove carbon dioxide released from the second monolith.

23. The system of claim **22**, further comprising a first vacuum pump in fluid communication with the first carbon dioxide outlet and a second vacuum pump in fluid communication with the second carbon dioxide outlet.

24-25. (canceled)

26. A method for extracting carbon dioxide from a fluid, the method comprising:
- flowing the fluid from a fluid source to a first chamber;
- contacting the fluid with a first sorbent disposed in the first chamber such that the first sorbent adsorbs carbon dioxide from the fluid;
- moving a closure to a first position to seal the first chamber, the closure being movable between the first position that seals the first chamber and a second position that seals a second chamber, the second chamber comprising a second sorbent disposed in the second chamber; and
- applying electric current to the first sorbent to heat the first sorbent to a predetermined temperature to extract carbon dioxide from the first sorbent.

27. The method of claim **26**, further comprising:
- flowing, when the closure is in the first position, the fluid from the fluid source to the second chamber; and
- contacting the fluid with the second sorbent such that the second sorbent adsorbs carbon dioxide from the fluid.

28. The method of claim **26**, further comprising:
- after applying the electric current to the first sorbent, moving the closure from the first position to the second position to unseal the first chamber and seal the second chamber; and
- applying the electric current to the second sorbent to heat the second sorbent to the predetermined temperature to extract carbon dioxide from the second sorbent.

29-33. (canceled)

34. The method of claim **26**, wherein the predetermined temperature is in a range of 80° C. to 200° C.

35. (canceled)

36. The method of claim **34**, wherein the predetermined temperature is 150° C.

37-39. (canceled)

40. A reactor for extracting carbon dioxide from a fluid, the reactor comprising:

an inlet configured to receive a fluid comprising carbon dioxide;

a first chamber comprising a first monolith configured to adsorb carbon dioxide from the fluid;

a second chamber comprising a second monolith configured to adsorb carbon dioxide from the fluid;

a closure slidably coupled to the reactor, the closure configured to slide between a first position that seals the first chamber and a second position that seals the second chamber; and

an electric conduit configured to:

apply electric current to the first monolith when the closure is in the first position to release carbon dioxide adsorbed by the first monolith; and

apply electric current to the second monolith when the closure is in the second position to release carbon dioxide adsorbed by the second monolith.

41-42. (canceled)

43. The reactor of claim **40**, wherein each of the first monolith and the second monolith comprises a metal carbonate.

44-46. (canceled)

47. The reactor of claim **40**, wherein a difference between a pressure of the fluid at the inlet and a pressure of the fluid at an outlet is in a range of 0.2 inches of water column to 1.1 inches of water column.

48-75. (canceled)

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