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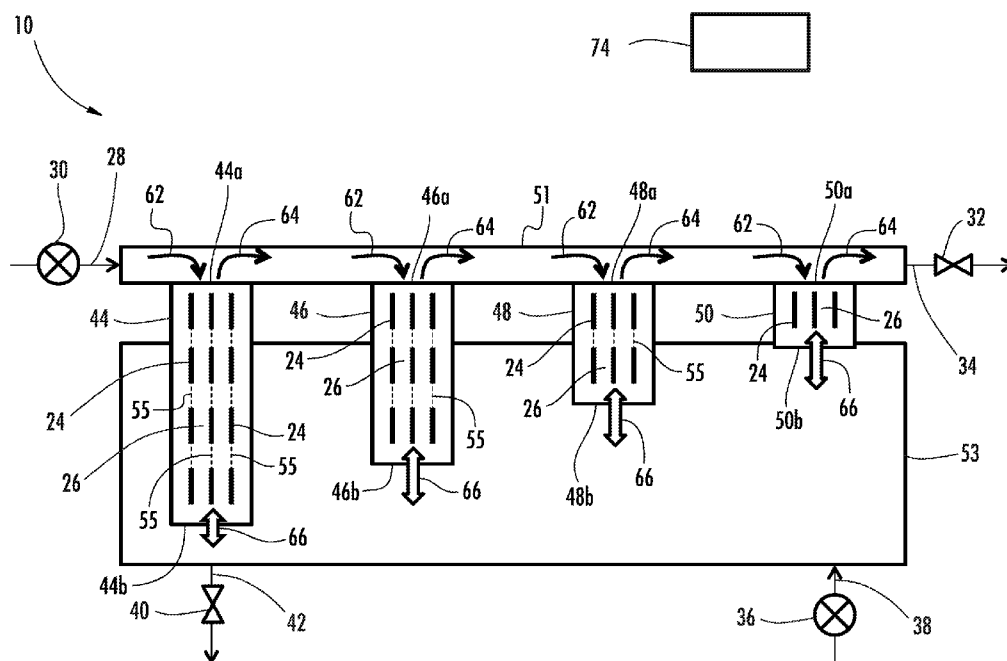


FIG. 1

(57) **Abstract:** A pyroelectric system (10) is disclosed that includes a plurality of pyroelectric modules (44, 46, 48, 50). The pyroelectric modules individually include a pyroelectric element, a first port (44a, 46a, 48a, 50a), a second port (44b, 46b, 48b, 50b), and an internal module fluid flow path (26) between the first port and the second port in thermal communication with the pyroelectric element. The pyroelectric modules are arranged along a cascade fluid flow path (51) connecting the first ports of the pyroelectric modules. A hot side inlet (28) to the cascade fluid flow path receives fluid at a first temperature from a heat source in fluid communication with the cascade fluid flow path, and the fluid is discharged from the cascade fluid flow path to a hot side outlet (34). A sink fluid flow path (53) comprises fluid at a second temperature lower than the first temperature, and is in fluid communication with the second ports of each of the plurality of pyroelectric modules.

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CASCADED PYROELECTRIC SYSTEM

BACKGROUND

[0001] This disclosure relates to pyroelectricity, and more specifically to pyroelectric systems to generate electrical power from heat.

[0002] The harvesting of solar, thermal, and mechanical energy is being pursued as alternative energy sources to conventional fossil fuels. Solar and mechanical energy sources have seen widespread use for electricity generation through solar panels and wind turbines. Thermal energy sources, on the other hand, have often focused on direct utilization of thermal energy such as geothermal heat transfer systems for residential and commercial heating and cooling. However, large amounts of waste heat from all sorts of commercial and consumer devices and processes are simply released without any attempt to harvest the energy.

[0003] Thermal energy harvesting research has largely focused on thermoelectrics. However, many thermoelectric materials and systems require large P-N junction temperature gradients, which can complicate the design of devices and has historically produced low efficiencies. Pyroelectricity is the ability of certain materials to generate surface charge and build a temporary voltage when they are heated or cooled. As opposed to thermoelectric materials which require a temperature gradient between two portions of the thermoelectric material to generate a charge, pyroelectric materials generate a charge and build a temporary voltage when the pyroelectric material changes temperature up or down over time. However, utilization of thermal streams having a varying temperature has not produced efficient electric power because such single-pass flow-through pyroelectric elements are subject to temperature swing dampening as fluid flow proceeds along the length of a pyroelectric element. Pyroelectric elements utilizing internal regeneration are able to create their own temperature swings by moving fluid back and forth between a heat sink and a heat source past the pyroelectric element; however, applying this approach with large temperature swings can subject the pyroelectric material to undesirable thermal stresses and can subject the pyroelectric material to voltage levels that run the risk of exceeding material breakdown limits.

[0004] Thus, due to this risk, existing pyroelectric systems are capable of utilizing only a small amount of temperature differential for energy generation, regardless of the temperature differential available; the remainder of the temperature differential is typically exhausted as unused waste heat.

BRIEF DESCRIPTION

[0005] In some embodiments of this disclosure, a pyroelectric system comprises a plurality of pyroelectric modules. The pyroelectric modules individually comprise a pyroelectric element, a first port, a second port, and an internal module fluid flow path between the first port and the second port in thermal communication with the pyroelectric element. The pyroelectric modules are arranged along a cascade fluid flow path connecting the first ports of the pyroelectric modules. A hot side inlet to the cascade fluid flow path receives fluid at a first temperature from a heat source in fluid communication with the cascade fluid flow path, and the fluid is discharged from the cascade fluid flow path to a hot side outlet. A sink fluid flow path comprises fluid at a second temperature lower than the first temperature, and is in fluid communication with the second ports of each of the plurality of pyroelectric modules.

[0006] In some embodiments, a method of generating electric power comprises

(i) directing fluid from a heat source at a first temperature to a cascade fluid flow path, and directing fluid from the cascade fluid flow path to hot side ports of a plurality of pyroelectric modules arranged along the cascade fluid flow path, displacing fluid from the pyroelectric modules through cold side ports of the plurality of pyroelectric modules to a sink fluid flow path comprising fluid at a second temperature lower than the first temperature;

(ii) directing fluid at the second temperature from the sink fluid flow path to the cold side ports of the plurality of pyroelectric modules, displacing fluid from the pyroelectric modules through hot side ports of the plurality of pyroelectric modules to the cascade fluid flow path; and

(iii) repeatedly alternating over time between (i) and (ii).

[0007] In any one or combination of the foregoing embodiments, the pyroelectric modules individually comprise a plurality of pyroelectric elements in a stack configuration in thermal communication with the module internal fluid flow path.

[0008] In any one or combination of the foregoing embodiments, at least one of the pyroelectric modules comprises a plurality of pyroelectric elements in series between first and second ports of the pyroelectric module.

[0009] In any one or combination of the foregoing embodiments, the sink fluid flow path comprises an inlet in fluid communication with a fluid source at a third temperature lower than the second temperature, an outlet, and a fluid mixing chamber in fluid communication with inlet, outlet, and the second ports of the plurality of pyroelectric modules

[0010] In any one or combination of the foregoing embodiments, the fluid source is outside ambient air.

[0011] In any one or combination of the foregoing embodiments, the cascade fluid flow path has thermal gradient that is hotter toward the hot side inlet and cooler toward the hot side outlet.

[0012] In any one or combination of the foregoing embodiments, the system further comprises a controller configured to selectively direct fluid communication and direction of fluid flow between the first ports of the plurality of pyroelectric modules and the cascade fluid flow path, to selectively direct fluid communication and direction of fluid flow between the second ports of the plurality of pyroelectric modules and the sink fluid flow path, and to selectively harvest electrical power from each of the plurality of pyroelectric modules.

[0013] In any one or combination of the foregoing embodiments, the controller is configured to alternatively operate the system in one of a first and a second mode of operation. In the first mode of operation, fluid is directed from the cascade fluid flow path to the first ports of the plurality of pyroelectric modules, displacing fluid on the internal module fluid flow paths through the second ports of the plurality of pyroelectric modules to the sink fluid flow path. In the second mode of operation, fluid is directed from the sink fluid flow path to the second ports of the plurality of pyroelectric modules, displacing fluid on the internal module fluid flow paths through the first ports of the plurality of pyroelectric modules to the cascade fluid flow path.

[0014] In any one or combination of the foregoing embodiments, the controller is configured to repeatedly operate, or the method comprises repeatedly operating, the system alternately in the first and second modes of operation to provide a back and forth regenerative fluid flow in the plurality of pyroelectric modules.

[0015] In any one or combination of the foregoing embodiments, wherein the controller is configured to displace, or the method comprises displacing, a volume of fluid in each mode of operation that is less than the fluid unit volume of each pyroelectric module.

[0016] In any one or combination of the foregoing embodiments, wherein the controller is configured to displace, or the method comprises displacing, a volume of fluid in each mode of operation that is less than half of the fluid unit volume of each pyroelectric module.

[0017] In any one or combination of the foregoing embodiments, the fluid comprises vapor of a material that is electrolytic in liquid form, and the fluid temperature in the system is maintained above a condensation temperature of the material.

[0018] In any one or combination of the foregoing embodiments, the system further comprises a third fluid flow path from the cascade fluid flow path outlet to the sink fluid flow path.

[0019] In any one or combination of the foregoing embodiments, the system further comprises a heat exchanger comprising a heat rejection side in communication with the cascade fluid flow path outlet, and a heat absorption side in fluid communication with the sink fluid flow path.

[0020] In any one or combination of the foregoing embodiments, the fluid comprises wherein the fluid comprises vapor of a material that is electrolytic in liquid form, and the fluid temperature in the system is maintained above a condensation temperature of the material.

[0021] In any one or combination of the foregoing embodiments, the method further comprises introducing fluid to the sink fluid flow path from a fluid source at a third temperature lower than the second temperature.

BRIEF DESCRIPTION OF THE DRAWINGS

[0022] Subject matter of this disclosure is particularly pointed out and distinctly claimed in the claims at the conclusion of the specification. The foregoing and other features, and advantages of the present disclosure are apparent from the following detailed description taken in conjunction with the accompanying drawings in which:

[0023] FIG. 1 is a schematic depiction of an example embodiment of a pyroelectric system;

[0024] FIG. 2A is a schematic depiction of the pyroelectric system of FIG. 1 in a first mode of operation;

[0025] FIG. 2B is a schematic depiction of the pyroelectric system of FIG. 1 in a second mode of operation;

[0026] FIG. 3 is a schematic depiction of an example embodiment of a pyroelectric system including a third fluid flow path; and

[0027] FIG. 4 is a schematic depiction of an example embodiment of a pyroelectric system including a heat exchanger.

DETAILED DESCRIPTION

[0028] As mentioned above, the pyroelectric modules comprise a pyroelectric element. In some embodiments, a pyroelectric element can comprise a pyroelectric material

fitted with electrical connections for harvesting electrical power generated by the pyroelectric material when it is subjected to changes in temperature. Pyroelectric materials are polar materials that exhibit a spontaneous polarization in the absence of an applied electric field. Spontaneous polarization can occur in ionically bonded materials where the polarization occurs as a consequence of the crystal structure. In crystalline polymers with aligned molecular chains, spontaneous polarization can derive from an alignment of polarized covalent bonds. The spontaneous polarization in the material leads to formation of a charge on surfaces of the material, which can attract free charges such as ions or electrons to the charged surfaces of the material. When a pyroelectric is heated or cooled ($dT/dt \neq 0$) there is a respective decrease or increase in the level of spontaneous polarization as dipoles within the material lose their orientation due to thermal vibrations. This leads to a change in the free charges at the surface, and an electrical potential difference as the free charges migrate toward or away from the charged surface of the material depending on whether the material is being cooled or heated. The temperature around which the transition in spontaneous polarization is experienced is referred to as the material's Curie temperature. Examples of pyroelectric materials include, but are not limited to crystalline materials such as, for example, lead zirconate titanate (PZT), lead magnesium niobate – lead titanate (PMN-PT), manganese doped bismuth sodium titanate–barium titanate (BNT-BT), triglycine sulphide (TGS), potassium sodium niobate ($(K_{0.5}Na_{0.5})NbO_3$) (KNN), as well as crystalline polymers such as polyvinylidene fluoride (PVDF), poly(vinylidene fluoride-co-trifluoroethylene) (P(VDF-TrFE)) or poly(vinylidene fluoride-co-trifluoroethylene-co-chlorofluoroethylene) (P(VDF-TrFE-CFE)). A person of skill in the art would understand that other pyroelectric materials are known. In some embodiments, the pyroelectric elements can be configured as thin films in order increase thermal response and avoid voltage material breakdown.

[0029] Thin films can be in some embodiments preferable because they have a faster thermal response, tend to have fewer defects and thus a higher breakdown strength such that at higher temperature differentials the material is less likely to break down, as follows. Because a thin film provides more heat transfer surface area and a shorter thermal time constant, thin films stacked with fluid space in between each film may allow the pyroelectric material within each film to more rapidly follow fluctuations in fluid temperature, as opposed to a thicker pyroelectric material which will follow temperature fluctuations more gradually. However, the optimum spacing between films may depend upon fluid density and film thickness, such that heat capacity of the film and fluid within the space are closely matched.

[0030] In some embodiments, pyroelectric film thickness can be in a range from having a lower limit of 0.1 μm , more specifically 0.5 μm , and even more specifically 1 μm , and an upper limit of 1000 μm , more specifically 100 μm , and even more specifically 10 μm . It is understood that these upper and lower range limits can be independently combined to disclose a number of different possible ranges. In some embodiments, multiple pyroelectric films can be disposed in the pyroelectric module housing in a stack configuration with space between the individual films for fluid flow. Thus, each element comprised of multiple films may be combined with other elements in a selective fashion to form a module, where each module may have elements with differing characteristics, tuned to temperature and hot fluid density conditions likely to be prevalent within that module and within that position in the stack of elements in the individual module. As described below, these modules may then be disposed in a cascade along a fluid flow path.

[0031] Additionally, as described in additional detail with regard to the Figures below, a plurality of modules, each module including a plurality of stacked thin-film elements, may be placed in a cascade along a cascade fluid flow path which receives a fluid flow from a heat source prior to the first module, with each module oscillating the flow path from the cascade fluid flow path to a heat sink and then reversing the flow back from the heat sink to the cascade fluid path such that the reversed and cooler flow from each previous module will mix with the cascade fluid path and subsequently enter the next module downstream within the cascade fluid path during the next flow oscillation cycle. As a result of this oscillation cycle, and also heat loss resulting from the harvesting of electricity from the pyroelectric elements, temperature will drop between each subsequent module in the cascade, as heat is drawn out by the previous module or modules due to the generation of electricity. Such a configuration enables the utilization of a higher proportion of the temperature differential between a high temperature source (e.g. 600 K – 2000K) and ambient sink temperature (e.g. 350 K – 250 K or lower) for the generation of energy than stacking multiple elements in a single fluid path where the output of one element is the input of another element downstream within a stack such that when flow is reversed the remaining hot fluid is exhausted to the ambient.

[0032] With reference now to the Figures, FIGS. 1, 2A, and 2B schematically depict an example embodiment of a pyroelectric system. As shown in the Figures, pyroelectric system 10 comprises pyroelectric modules 44, 46, 48, and 50, which include multiple pyroelectric elements 24 (as used herein, the term “pyroelectric element” refers to a discrete segment of pyroelectric material such as a segment of a film of pyroelectric material) with

module internal fluid flow path 26 in the spaces between the pyroelectric elements 24. The pyroelectric modules each have a first port 44a, 46a, 48a, and 50a, connecting the respective pyroelectric module to cascade fluid flow path 51 in fluid communication with inlet 28, which receives a fluid flow at a first temperature from a heat source (not shown), in some embodiments driven by an optional first pumping device 30 such as a fan, blower, pump, or similar device. Pressure in the cascade fluid flow path can be controlled by the output of pumping device 30 and/or by optional pressure control valve 32 disposed at cascade fluid flow path outlet 34. The pyroelectric modules also have second ports 44b, 46b, 48b, and 50b connecting them to sink fluid flow path 53 comprising fluid at a second temperature lower than the first temperature. Sink fluid flow path 53, although depicted in the Figures as a single path, may be a non-flowing constant temperature plenum, or multiple paths or plena, each in communication with one or more of the stacked modules, such that each module is in connection with at least one sink flow or plenum. Fluid in the sink fluid flow path 53 can be controlled to a target pressure by an optional second pumping device 36 at sink flow path inlet 38, and/or an optional pressure control valve 40 at sink flow path outlet 42. In some embodiments, as shown in the Figures, the heat sink fluid flow path 53 can be configured as a mixing chamber fluid in which fluid can be controlled to a target temperature (e.g., a third temperature greater lower than the first temperature and greater than the second temperature) by appropriate adjustment of the inlet and outlet flows through sink flow path inlet 38 and sink flow path outlet 42.

[0033] As shown in FIGS. 1, 2A, and 2B, the pyroelectric modules are arranged in a cascade configuration from the cascade flow path inlet 28 to the cascade flow path outlet 34, with pyroelectric module 44 disposed closest to the inlet and furthest from the outlet, and pyroelectric module 50 disposed closest to the outlet and furthest from the inlet. Fluid flow paths in and out of the pyroelectric modules through the ports are depicted by the arrows 62, 64, and 66. It should be noted that although the cascade fluid flow path 51 is depicted as a single conduit, it could also be comprised of multiple separate conduits providing flow connections as depicted by the unnumbered arrows. A controller 74 is in communication with electrical connections and circuitry (not shown) that harvest electricity from the pyroelectric elements during operation of the system, and is also in communicative control with the fluid flow shut-offs, and various pumps, fans, valves, and other fluid processing equipment (not shown) to move fluid through the system as described in more detail below.

[0034] During operation, as shown in FIG. 2A, the system can operate in a first mode where hot fluid from the heat source (e.g., a combustion exhaust) is available at the inlet 28.

In the first mode of operation, fluid on the cascade fluid flow path 51 is controlled to a pressure greater than pressure in sink fluid flow path 53 such that fluid flows in the direction of the arrows 62, 66 in FIG. 2A from the cascade fluid flow path 51 through the first ports 44a, 46a, 48a, 50a of the pyroelectric modules through the module internal fluid flow paths 26, displacing fluid within the module internal fluid flow paths 26 through the second ports 44b, 46b, 48b, 50b of the pyroelectric modules and into the sink fluid flow path 53. Of course, the control of pressure in the cascade fluid flow path 51 and the sink fluid flow path 53 is an illustrative example of controlling the direction of fluid flow through the pyroelectric modules, and other fluid flow control means such as control valves, check valves, or other passive flow control means can be used as well. In this first mode of operation, the pyroelectric modules are in a heat regenerative mode where they receive heat from the sink fluid flow path 51. The concomitant rise in temperature produces an electric current from the pyroelectric elements that is harvested by current collectors (not shown) disposed at the pyroelectric material surface.

[0035] During operation, as shown in FIG. 2B, the system can operate in a second mode where pressure in the sink fluid flow path 53 is controlled to a pressure greater than the pressure in the cascade fluid flow path 51. In the second mode of operation, fluid flows in the direction of the arrows 64, 66 in FIG. 2B from the sink fluid flow path 53 through the second ports of the pyroelectric modules to the module internal fluid flow paths 26, displacing fluid on the module internal fluid flow paths 26 through the first ports of the pyroelectric modules and into the cascade fluid flow path 51. In this second mode of operation, the pyroelectric modules are in a thermal discharge mode. The concomitant drop in temperature produces an electric current from the pyroelectric elements that is harvested by current collectors (not shown) disposed at the pyroelectric material surface.

[0036] As can be seen by a comparison of FIGS. 2A and 2B, each pyroelectric module undergoes internal thermal regeneration with a back and forth fluid flow between a hot side toward the module first port and the relatively hotter cascade fluid flow path 51, and a cold side toward the module second port and the cooler sink fluid flow path 53. In some embodiments, the volume of fluid displaced in each pyroelectric module during each operational mode is less than the volume of the module internal fluid flow path, and in some embodiments less than half the volume of the module internal fluid flow path.

[0037] Additionally, each pyroelectric module in the cascade will have successively lower hot side temperatures proximate to the first ports compared to the adjacent module closer to the inlet 28, providing a thermal gradient along the cascade fluid flow path 51 that is

hotter toward the cascade fluid flow path inlet 28 and cooler toward the cascade fluid flow path outlet 34. The thermal gradient can result from progressive convective heat transfer through the back and forth regenerative fluid flow through the pyroelectric modules, and/or from heat loss as electricity is harvested from the pyroelectric elements. In sequence, hot fluid enters the pyroelectric module 44 and heats up the material, with the fluid in the module near the first port 44a, reaching an equilibrium that is slightly below the inlet fluid temp. As electric power is pulled out of the material, the material and thus fluid are additionally cooled. When the fluid flow is reversed, the now cooler fluid is ejected back into the cascade fluid path where it mixes with the hotter fluid and reduces the overall cascade fluid temperature. This cooled cascade fluid flows downstream along with the general flow direction moving from the cascade fluid flow path inlet 28 to the cascade fluid flow path outlet 34 so it reaches the next module in the cascade. The second module thus pulls in cooler fluid than the first module and the process repeats itself as many times as necessary to reduce the cascade fluid to the desired temperature. The thermal gradient on the cascade fluid flow path 51 means that each successive pyroelectric module in the cascade will receive fluid from the cascade fluid flow path at a lower temperature than the next adjacent pyroelectric module toward the cascade fluid flow path inlet 28, and will therefore have a successively smaller temperature difference between the first and second port compared to the adjacent module closer to the cascade flow path inlet 28. In other words, the temperature difference between the first and second port will be the greatest for pyroelectric module 44, with a smaller temperature difference for pyroelectric module 46, and successively smaller temperature differences for pyroelectric modules 48 and 50.

[0038] In some embodiments, as depicted in FIGS. 1, 2A, and 2B, the pyroelectric modules can have pyroelectric elements within each module arranged in series (e.g., along dashed lines 55), with the pyroelectric elements in the series closer to the first port and cascade fluid flow path 51 having pyroelectric materials tuned (tuned with respect to material thickness or material composition) to have optimal performance (a combination of breakdown strength and electricity generation) to a higher temperature, and the elements in the series being tuned to have higher performance at progressively lower temperatures as they get closer to the second port and the sink fluid flow path 53.

[0039] In some embodiments, as depicted in FIGS. 1, 2A, and 2B, pyroelectric modules having a greater temperature difference between the module's first and second ports can have a longer series of pyroelectric elements to help maintain voltage differential and thermal stress on the individual pyroelectric elements within operational parameters to avoid

material fatigue or electrical breakdown. In some embodiments, fluid displacement within each of the pyroelectric modules can be equal among the pyroelectric modules. This can be accomplished for example, by providing the shorter pyroelectric modules closer to the cascade fluid flow path outlet 34 with a greater cross-sectional area (compared to the modules closer to the cascade fluid flow path inlet 28) to provide equal module internal fluid flow path volumes among the pyroelectric modules. In some embodiments, the shorter pyroelectric modules closer to the cascade fluid flow path outlet 34 can have smaller module internal fluid flow path volumes, while partial fluid displacement of the module internal fluid flow path volume is maintained for each of the pyroelectric modules by fluid flow shut-offs at the first and second ports so that fluid flow can be terminated earlier during each operational mode for the shorter pyroelectric modules compared to the longer pyroelectric modules (e.g. where the volume of a module is less, a shut-off is provided so that the fluid flow can be stopped when enough fluid has passed through the module, which requires less flow relative to larger-volume modules earlier in the stream). In embodiments having multiple pyroelectric elements in series within a module the pyroelectric elements will typically be physically separated, with each pyroelectric element having its own charge collectors. Physical separation of the pyroelectric films specifically in the axial direction (e.g. flow direction), particularly in a stacked configuration, may also improve system efficiency by minimizing heat conduction in the axial direction from the hot side cascade fluid flow path 51 to the cold side sink fluid flow path 53.

[0040] Unlike other proposed regenerative pyroelectric systems, direct entry of outside ambient fluid into the pyroelectric modules is not needed because the cold-side sink fluid flow path 53 acts as a thermal buffer, in which the temperature of the sink fluid can be higher than the outside ambient temperature. This can help promote avoidance of excessively cool temperatures in the pyroelectric modules (e.g., from direct outside ambient air) that could cause condensation of water vapor or other vapor that is electrolytic in liquid form that can damage the pyroelectric circuits. In some embodiments, fluid temperatures in the system are maintained above a condensation temperature of any material that could condense to form an electrolytic liquid. In some embodiments, as shown in FIG. 3, heat can be provided to the sink fluid flow path by a third fluid flow path 57 from the cascade fluid flow path outlet 34 to the sink fluid flow path inlet temperature in the sink fluid flow path 53, with control valves 32 and 59 being operated to direct all or a portion of the cascade fluid flow path output to the sink fluid flow path 53. In some embodiments, as shown in FIG. 4, heat can be provided to the sink fluid flow path by a heat exchanger 61 a heat rejection side in communication

through control valve 59 with the cascade fluid flow path outlet 34, and a heat absorption side in fluid communication with the sink fluid flow path inlet 38. All other numbered components in FIGS. 3 and 4 are the same as those in FIGS 1, 2A, and 2B, and do not require repetition here. In some embodiments, the system can be designed with a number of pyroelectric modules and operational parameters (e.g., fluid flow rates and duration of cycling between the first and second modes of operation) to maintain the fluid in the sink fluid flow path 53 to just above the fluid dew point, thus harvesting essentially all of the thermal energy that can feasibly be harvested without producing condensate.

[0041] While the present disclosure has been described in detail in connection with only a limited number of embodiments, it should be readily understood that the present disclosure is not limited to such disclosed embodiments. Rather, the present disclosure can be modified to incorporate any number of variations, alterations, substitutions or equivalent arrangements not heretofore described, but which are commensurate with the spirit and scope of the present disclosure. Additionally, while various embodiments of the present disclosure have been described, it is to be understood that aspects of the present disclosure may include only some of the described embodiments. Accordingly, the present disclosure is not to be seen as limited by the foregoing description, but is only limited by the scope of the appended claims.

CLAIMS:

1. A pyroelectric system, comprising:
 - a plurality of pyroelectric modules that individually comprise a pyroelectric element, a first port, a second port, and an internal module fluid flow path between the first port and the second port in thermal communication with the pyroelectric element, the plurality of pyroelectric modules arranged along a cascade fluid flow path connecting the first ports of the pyroelectric modules;
 - a hot side inlet receiving fluid at a first temperature from a heat source in fluid communication with the cascade fluid flow path, and a hot side outlet;
 - a sink fluid flow path comprising fluid at a second temperature lower than the first temperature, the sink fluid flow path in fluid communication with the second ports of each of the plurality of pyroelectric modules.
2. The system of claim 1, wherein the pyroelectric modules individually comprise a plurality of pyroelectric elements in a stack configuration in thermal communication with the module internal fluid flow path.
3. The system of claims 1 or 2, wherein at least one of the pyroelectric modules comprises a plurality of pyroelectric elements in series between first and second ports of the pyroelectric module.
4. The system of any of claims 1-3, wherein the sink fluid flow path comprises an inlet in fluid communication with a fluid source at a third temperature lower than the second temperature, an outlet, and a fluid mixing chamber in fluid communication with inlet, outlet, and the second ports of the plurality of pyroelectric modules.
5. The system of claim 4, wherein the fluid source is outside ambient air.
6. The system of any of claims 1-5, wherein the cascade fluid flow path has thermal gradient that is hotter toward the hot side inlet and cooler toward the hot side outlet.
7. The system of any of claims 1-6, further comprising a controller configured to selectively direct fluid communication and direction of fluid flow between the first ports of the plurality of pyroelectric modules and the cascade fluid flow path, to selectively direct fluid communication and direction of fluid flow between the second ports of the plurality of pyroelectric modules and the sink fluid flow path, and to selectively harvest electrical power from each of the plurality of pyroelectric modules.
8. The system of claim 7, wherein the controller is configured to alternatively operate the system in one of a first and a second mode of operation;

wherein in the first mode fluid is directed from the cascade fluid flow path to the first ports of the plurality of pyroelectric modules, displacing fluid on the internal module fluid flow paths through the second ports of the plurality of pyroelectric modules to the sink fluid flow path; and

wherein in the second mode fluid is directed from the sink fluid flow path to the second ports of the plurality of pyroelectric modules, displacing fluid on the internal module fluid flow paths through the first ports of the plurality of pyroelectric modules to the cascade fluid flow path.

9. The system of claim 8, wherein the controller is configured to repeatedly operate the system alternately in the first and second modes of operation to provide a back and forth regenerative fluid flow in the plurality of pyroelectric modules.

10. The system of claims 8 or 9, wherein the controller is configured to displace a volume of fluid in each mode of operation that is less than the fluid unit volume of each pyroelectric module.

11. The system of claim 10, wherein the controller is configured to displace a volume of fluid in each mode of operation that is less than half of the fluid unit volume of each pyroelectric module.

12. The system of any of claims 1-11, wherein the fluid comprises vapor of a material that is electrolytic in liquid form, and the fluid temperature in the system is maintained above a condensation temperature of the material.

13. The system of any of claims 1-12, further comprising a third fluid flow path from the cascade fluid flow path outlet to the sink fluid flow path.

14. The system of any of claims 1-12, further comprising a heat exchanger comprising a heat rejection side in communication with the cascade fluid flow path outlet, and a heat absorption side in fluid communication with the sink fluid flow path.

15. A method of generating electric power, comprising:

(i) directing fluid from a heat source at a first temperature to a cascade fluid flow path, and directing fluid from the cascade fluid flow path to hot side ports of a plurality of pyroelectric modules arranged along the cascade fluid flow path, displacing fluid from the pyroelectric modules through cold side ports of the plurality of pyroelectric modules to a sink fluid flow path comprising fluid at a second temperature lower than the first temperature;

(ii) directing fluid at the second temperature from the sink fluid flow path to the cold side ports of the plurality of pyroelectric modules, displacing fluid from the pyroelectric

modules through hot side ports of the plurality of pyroelectric modules to the cascade fluid flow path; and

(iii) repeatedly alternating over time between (i) and (ii).

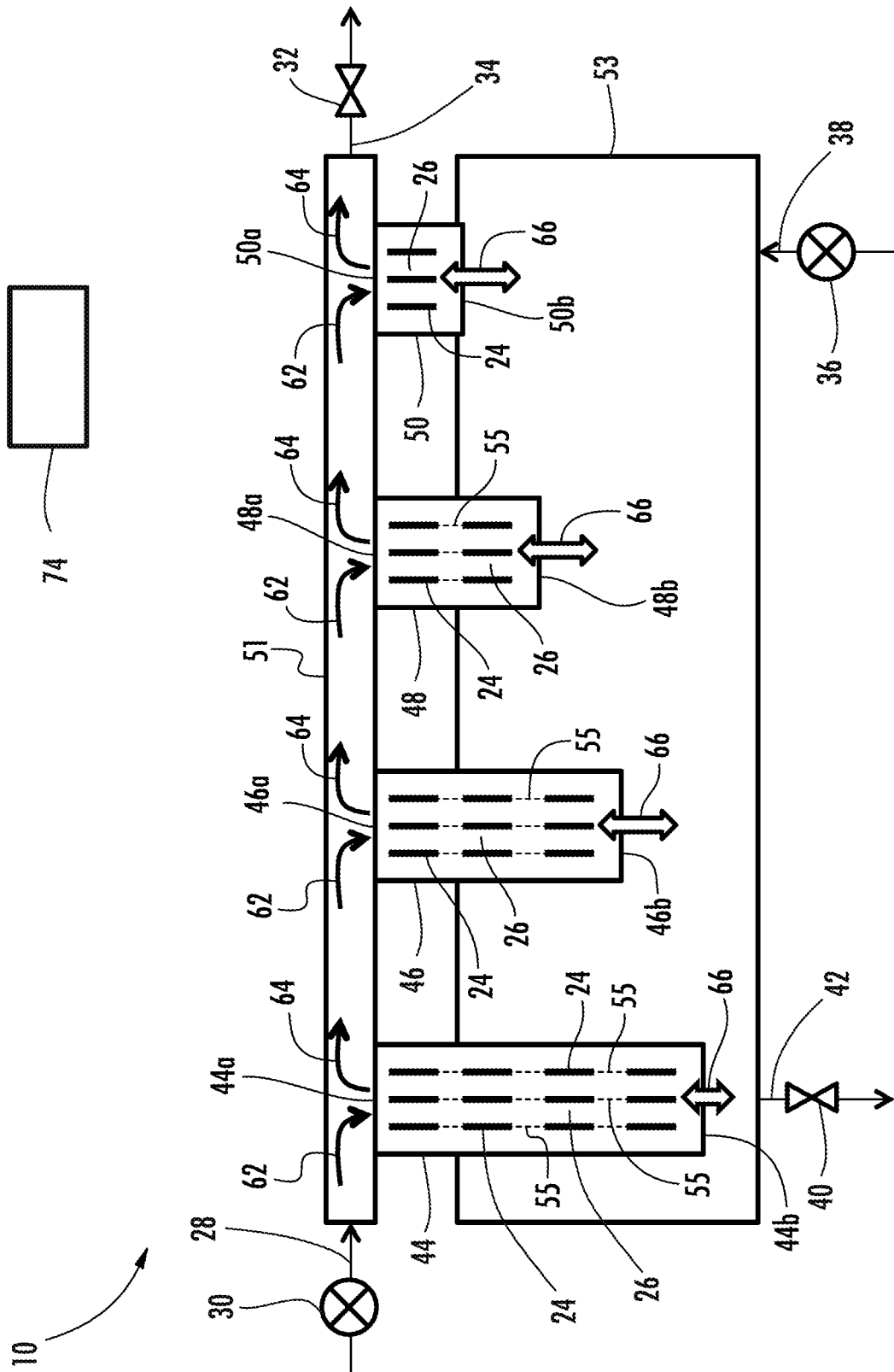
16. The method of claim 15, wherein alternating between (i) and (ii) produces a back and forth fluid flow in the pyroelectric modules for internal heat regeneration.

17. The method of claims 15 or 16, wherein the volume of fluid displaced in (i) and (ii) is less than the fluid unit volume of each pyroelectric module.

18. The method of claim 17, wherein the volume of fluid displaced in (i) and (ii) is less than half of the fluid unit volume of each pyroelectric module.

19. The method of any of claims 15-18, wherein the fluid comprises wherein the fluid comprises vapor of a material that is electrolytic in liquid form, and the fluid temperature in the system is maintained above a condensation temperature of the material.

20. The method of any of claims 15-20, further comprising introducing fluid to the sink fluid flow path from a fluid source at a third temperature lower than the second temperature.



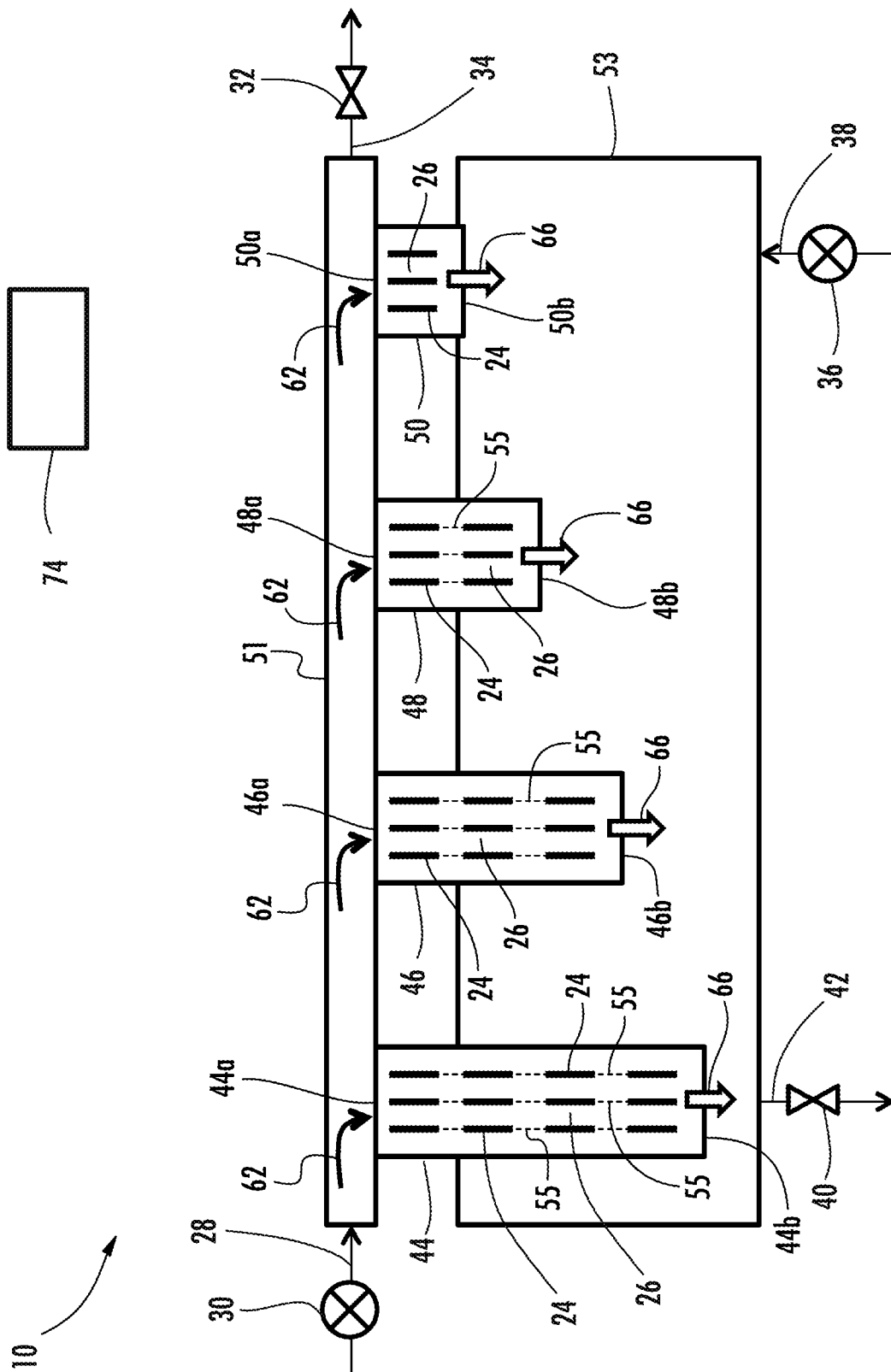


FIG. 2A

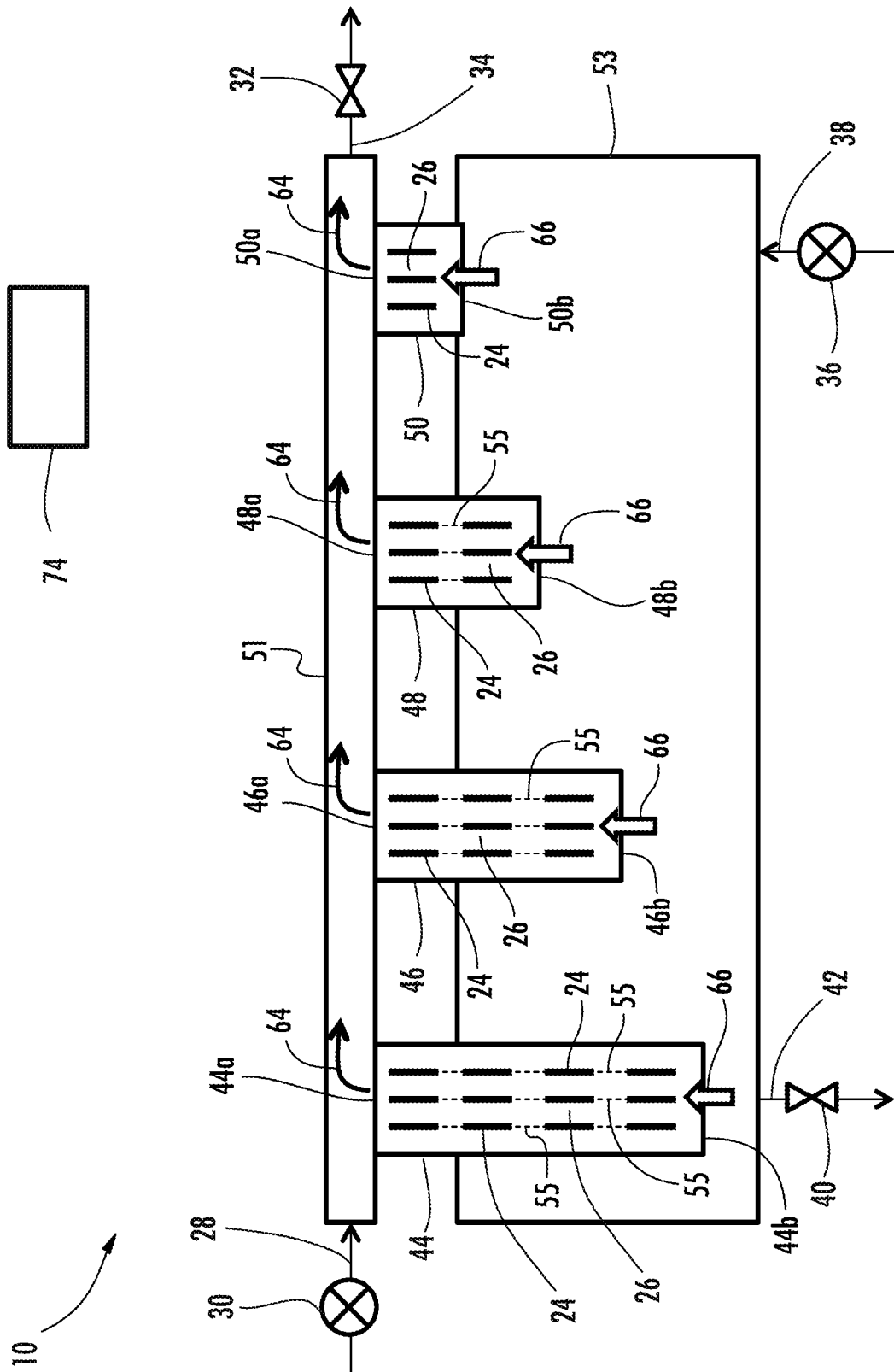


FIG. 2B

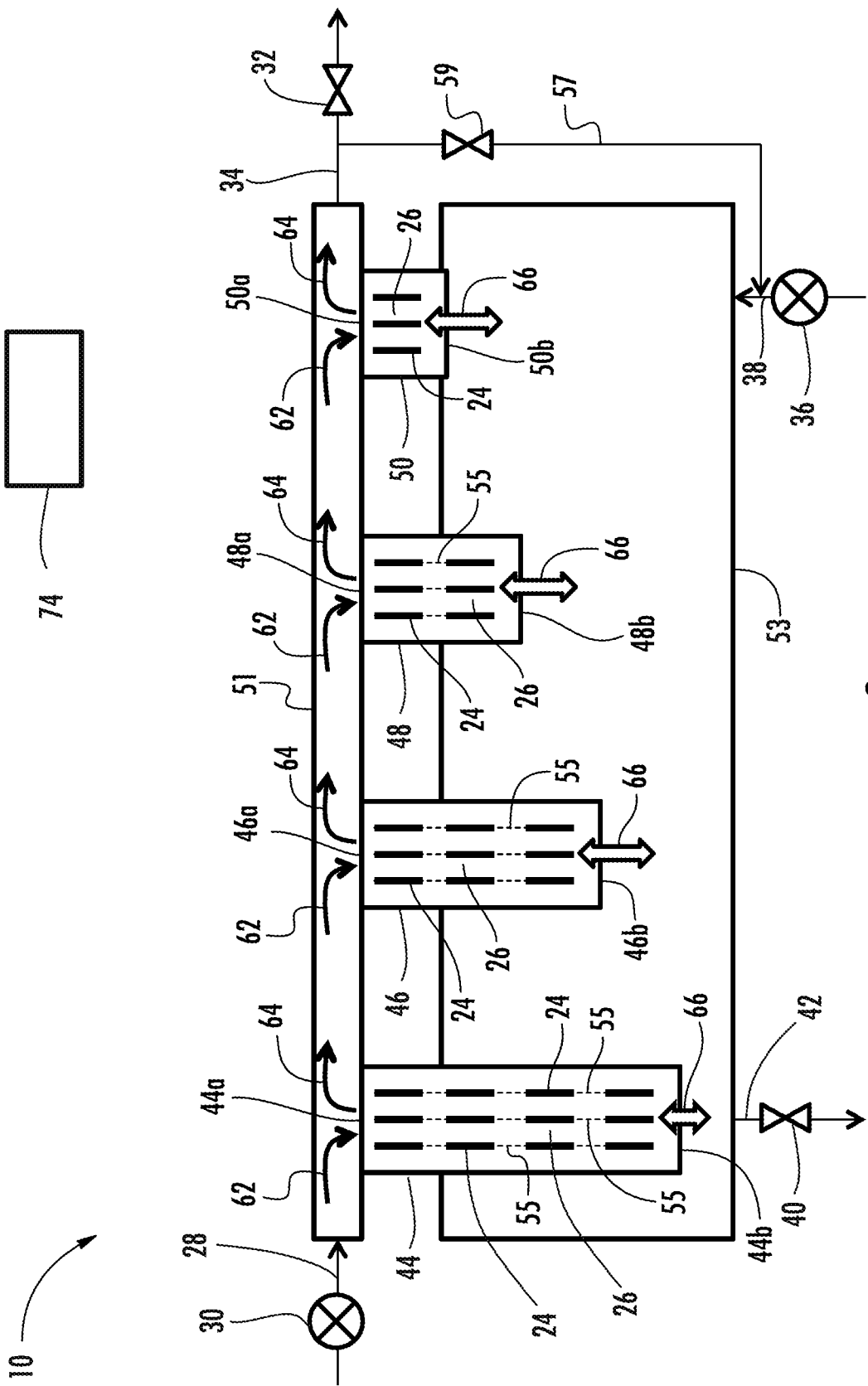


FIG. 3

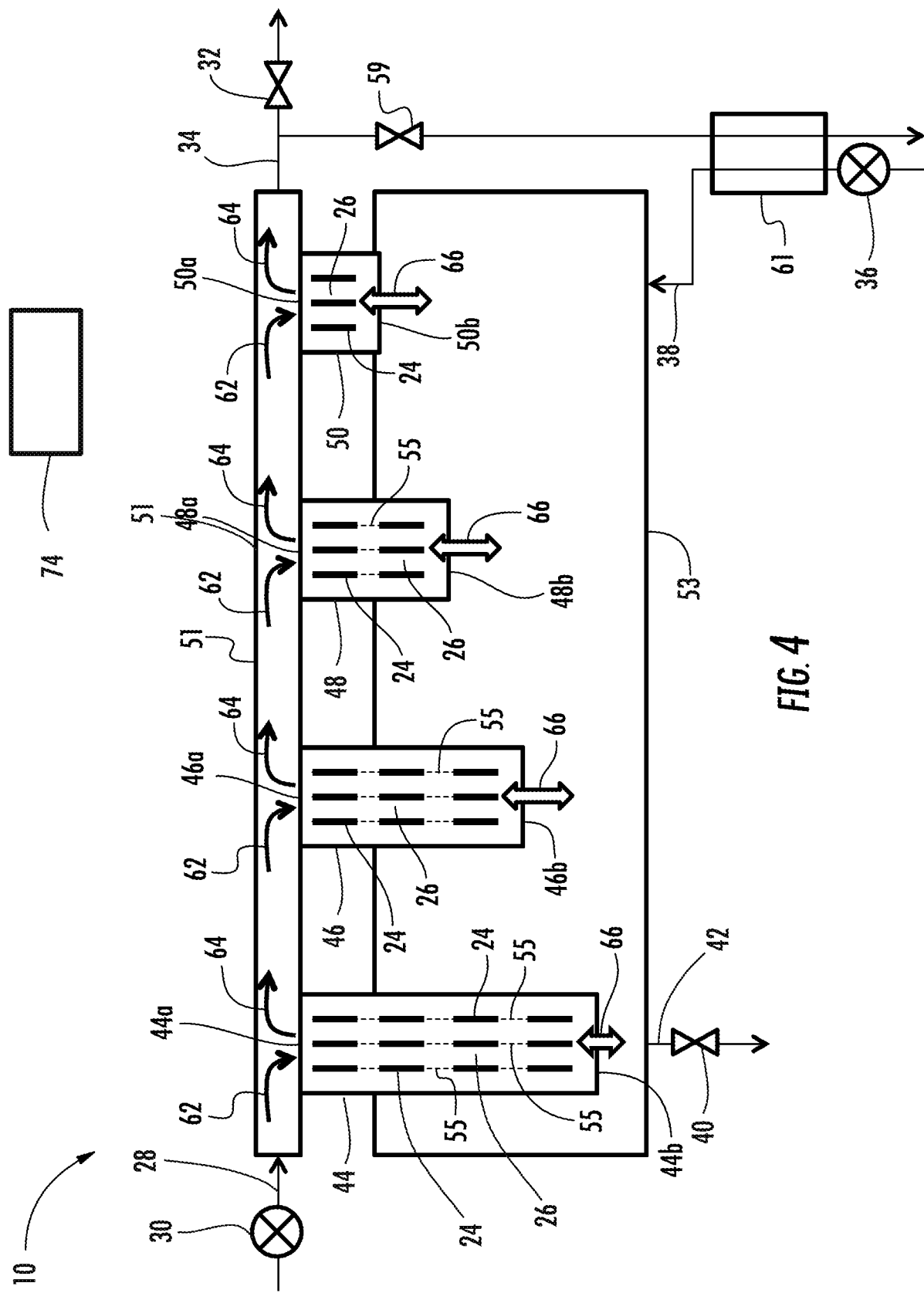


FIG. 4

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2016/047157

A. CLASSIFICATION OF SUBJECT MATTER

INV. H01L37/02

ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H01L

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

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

EPO-Internal, INSPEC, COMPENDEX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	OLSEN R B ET AL: "Cascaded pyroelectric energy converter", FERROELECTRICS, TAYLOR & FRANCIS INC, US, vol. 59, no. 3-4, 1 September 1984 (1984-09-01), pages 205-219, XP009194209, ISSN: 0015-0193, DOI: 10.1080/00150198408240091 page 206, line 1 - page 219, line 16; figures 1-12	1-20
X	FR 2 952 230 A1 (DELAHAYE THIERRY [FR]) 6 May 2011 (2011-05-06) page 9, line 32 - page 12, line 7; figures 3-7 ----- -/--	1-6,12



Further documents are listed in the continuation of Box C.



See patent family annex.

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

"&" document member of the same patent family

Date of the actual completion of the international search

28 April 2017

Date of mailing of the international search report

11/05/2017

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Gröger, Andreas

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2016/047157

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 00/36656 A1 (UNITED KINGDOM GOVERNMENT [CA]; IKURA MICHIO [CA]; CHARBONNEAU ROBERT) 22 June 2000 (2000-06-22) page 4, line 27 - page 8, line 2; figures 1-5 -----	1,2,4-6

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2016/047157

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			FR 2952230 A1 06-05-2011
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			EP 1145333 A1 17-10-2001
			JP 3955437 B2 08-08-2007
			JP 2002532906 A 02-10-2002
			US 6528898 B1 04-03-2003
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