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(54) **FLUID COOLED RADAR SYSTEM**

(57) A radar system comprising a stack of functional printed circuit boards arranged in layers, housed in a common enclosure, in which the stack of functional printed circuit boards layers comprises at least two sub-stacks and at least two cooling plates, wherein each of the cooling plates is in thermal contact with one of the sub-stacks, and wherein at least two cooling plates are thermally connected with each other by cooling fluid transferring means and are connected to a heat sink external to the common enclosure.

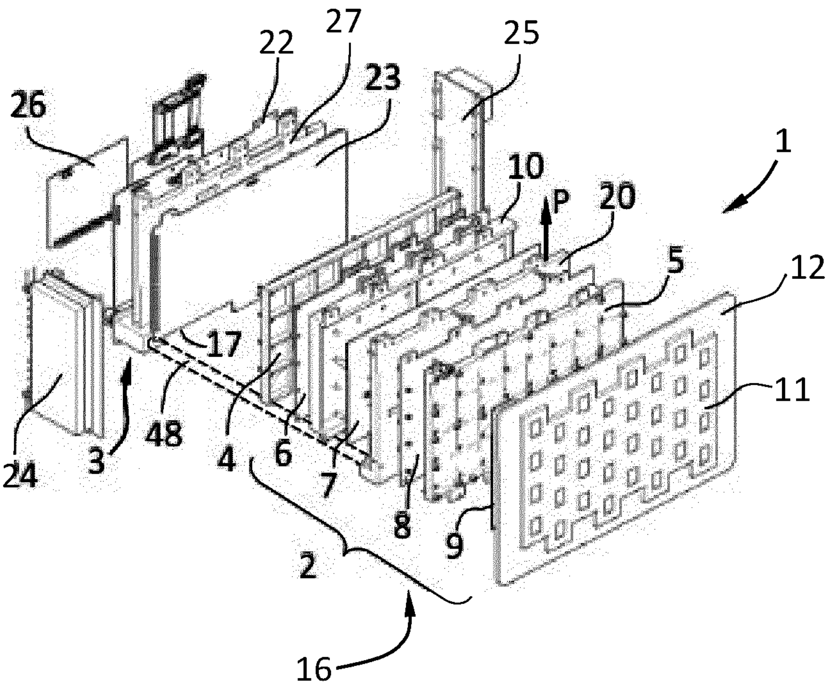

Fig. 1

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Description

[0001] The present invention provides a radar system with an improved cooling solution that saves on volume and offers modularity for use.

[0002] The invention pertains to the field of cooling radar components, specifically the cooling of active electronically scanned array radars (AESA radars) and other phased array radar types.

[0003] AESA radars are well known in the art and are widely used in civil and military applications.

[0004] AESA radars may be used in airborne, naval or terrestrial installations; in particular, terrestrial installations include static installation, in buildings or the like, and mobile installation, on vehicles or the like.

[0005] In such radars the various active components are mounted on printed circuit boards (PCB). During use many of the PCB mounted components produce an amount of heat which require cooling in order to enable the components to remain operational.

[0006] Modern AESA radars usually comprise a stack of individual or laminated layers, in particular layers of PCBs, each of which comprising a multitude of electronic and electric components such as different digital and analog chips and chipsets, RF transceiver and receivers, resistors, transistors, diodes, capacitors and other mounted components.

[0007] Other functional layers such as passive layers dedicated to shielding the circuits can also be present within the stack.

[0008] Such close packing of components in a stack produces an excess amount of heat, which requires an efficient heat removal capability.

[0009] US9172145 discloses an active electronically scanned array (AESA) radar system, comprising a stack of laminated PCBs. The system further comprises a heat sink having a surface configured to be in thermal contact with a plurality of electronics (i.e. both passive and active circuits) disposed on an external surface of a multilayer mixed signal printed wiring board (PWB). A second surface of the heat sink is provided with plurality of heat spreading elements such as fins, in order to remove excess heat from the entirety of the stack.

[0010] The applicant observes that, because of the different cooling efficiencies on the PCBs, due to their distance to the cooling plate, components that are in direct contact with the cooling plate will be cooled more efficiently than any components located on the opposing side of the stack, far from the cooling plate. The presence of heat spreading elements such as fins on one of the heat sink surfaces requires such heat sink to be exposed to air or the like, and increases bulkiness of the assembly. Additionally, this approach is believed to be generally feasible for radar systems of lower power consumption only, due to the restricted heat removal capabilities the single cooling plate offers, and likely not even possible in case of high-power systems, such as an 800W system.

[0011] US6292364 discloses a radar system and a cooling method including spray cooling of the relevant modules.

[0012] The patent application US2022272846 discloses a radar system including two circuit boards, for antenna elements and power circuitry, wherein the two circuit boards are mounted on opposite sides of a heat sink. The heat sink has internal channels providing pathways for a coolant fluid such as air or water, connected into a coolant system comprising a pump or fan and optionally a heat exchanger which is separate from the heat sink.

[0013] The patent application US2005146479 discloses a low profile active electronically scanned antenna for radar systems comprising an array of beam control tiles, wherein cooling of the various components is achieved by a pair of planar forced air heat sink members located on either side of the array of beam control tiles.

[0014] A problem of the prior art solutions is to provide an effective cooling of the various components of a radar system, even in case of high-power systems, without increasing the overall size of the system and by maintaining the electronic circuitry protected from external environment.

[0015] A stacked architecture of a radar system enables to achieve high compactness of construction, but this construction prevents the heat generated in the stack from being effectively dissipated; a further problem is in that the stacked architecture may prevent the cooling element from extending close to each of the active components, i.e. the components suitable to generate heat in operation, in order to provide an effective cooling effect, without interfering with the overall architecture and size of the system.

[0016] Within the scope of the present invention, it has been found that a radar system, and particularly a high power radar system, can efficiently manage with dissipation of the internally generated heat by arranging the system components into stacks of layers and by grouping the heat generating components into separate analog and digital heat generating sub-stacks, and arranging a dedicated cooling plate in close proximity with each of such heat generating sub-stacks and thermally connected with an external heat sink, such that the system can be tightly enveloped and protected against external environment.

[0017] The present invention concerns a radar system comprising a stack of functional printed circuit boards arranged in layers, housed in a common enclosure, in which the stack of functional printed circuit boards layers comprises at least two sub-stacks and at least two cooling plates, wherein each of the cooling plates is in thermal contact with one of the sub-stacks, and wherein at least two cooling plates are thermally connected with each other by cooling fluid transferring means and are connected to a heat sink external to the common enclosure.

[0018] In this description and in the attached claims, by cooling plate we mean a plate having substantially flat surfaces having the ability of absorbing heat from an element in contact or in close proximity therewith, and conveying such absorbed heat to an external means.

[0019] Preferably, the heat transferring means connecting the cooling plates are arranged within the external outline of the stack of functional layers.

[0020] Preferably, the stack of functional layers comprises an analog sub-stack and a digital sub-stack and the cooling plates comprise an analog cooling plate and a digital cooling plate, respectively in thermal contact with the analog sub-stack and the digital sub-stack.

[0021] In this description and in the attached claims, by analog sub-stack we mean a group of layers of functional printed circuit boards which contain analogically operating electric components; by digital sub-stack we mean a group of layers of functional printed circuit boards which contain digitally operating electric components.

[0022] Preferably, the analog sub-stack comprises at least an analog receiver, an electrical power controller, a solid-state power amplifier and an antenna.

[0023] Preferably, the digital sub-stack comprises at least a radar control circuit, a digital signal processor, a radio frequency distributor, a reference signal generator and a power distribution unit.

[0024] Preferably, the analog cooling plate and the digital cooling plate are hydraulically connected in series.

[0025] Preferably, the common enclosure is air and water tight.

[0026] Preferably, at least one of the functional printed circuit boards comprises electrical connectors arranged on one side only of the board whereby the board is capable of being dismantled from the stack independently of the adjacent boards.

[0027] Preferably, at least one of the functional printed circuit boards comprises an open cutout, around a cooling fluid transferring means and/or an electric connecting element.

[0028] In another aspect the present invention concerns a method of cooling a radar system comprising the steps of:

- arranging the active components of the radar system in one or more functional layers arranged in a stack,
- providing at least a first and a second cooling plate, wherein said first cooling plate is in thermal exchange contact with at least one of the functional layers of the stack and wherein said second cooling plate is in thermal exchange contact with at least another one of the functional layers of the stack;
- removing heat from one or more functional layers by said first cooling plate;
- removing heat from one or more functional layers by said second cooling plate, and
- transporting heat from at least one of said first and second cooling plate to a heat sink.

[0029] Preferably, the method comprises grouping the functional layers of the stack in at least two sub-stacks, wherein one of said sub-stacks groups at least some of the functional elements of analog type and another one of said sub-stacks groups at least some of the functional elements of digital type, and contacting each of said sub-stacks with one of said first and second cooling plates.

[0030] Preferably, the method comprises flowing a cooling fluid through said first and second cooling plates.

[0031] More preferably, the method comprises flowing the cooling fluid through the cooling plate contacting the sub-stack grouping analog type functional elements and then through the cooling plate contacting the sub-stack grouping digital type functional elements.

[0032] Preferably, the method comprises circulating a cooling fluid through said first and a second cooling plate and through an external heat sink.

[0033] Preferably, the cooling fluid is water.

[0034] More details will be identified from the following description of one embodiment, with reference to the enclosed figures, wherein it is shown:

in figure 1 an exploded view of a radar system according to the invention;

in figure 2 a plan view of the radar system of figure 1;

in figure 3 a perspective view of the active components of the radar system of figure 1 assembled together, seen from the lower side;

in figure 4 a perspective view of the radar system of figure 1;

in figure 5 a plan, cross-sectional view of the cooling plate of the digital sub-stack of the radar system;

in figure 6 a plan, cross-sectional view of the cooling plate of the analog sub-stack of the radar system;

in figure 7 a perspective view of the components of the radar system, with cooling plates in series connection;

in figure 8 a perspective view of an exemplary embodiment of the flow paths of the cooling plates in series connection;

in figure 9 a perspective view of the components of the radar system, with cooling plates in parallel connection;

in figure 10 a perspective view of an exemplary embodiment of the flow paths of the cooling plates in parallel connection;

in figure 11 a scheme of connection of a plurality of radar systems to a common heat sink.

[0035] As shown in figure 1, 2, 3 and 4, a radar system 1 comprises several functional layers, consisting substantially in printed circuit boards (PCB), arranged in a stacked configuration.

[0036] Preferably, the stack of said functional PCB layers has an essentially rectangular cuboid or cylindrical outline.

[0037] The stack of PCB functional layers comprises two sub-stacks, namely an analog sub-stack 2 and a digital sub-stack 3.

[0038] The function of the analog sub-stack 2 is to generate and receive radar signals, at different wavelengths and power levels, according to the operational needs. The main function of the digital sub-stack 3 is to control the operation of the analog sub-stack 2 and to process the received radar signals.

[0039] The analog sub-stack 2 includes two shielding layers 4, 5, an analog receiver (ARX) layer 6, an electrical power controller (EPC) layer 7, a solid-state power amplifier (SSPA) layer 8, a calibration layer 9, a thermal carter 10 and an antenna 11 adapted to send and receive radar signals, supported by an antenna support 12.

[0040] The analog sub-stack 2 further includes a liquid-cooled cooling plate 20, in thermal exchange contact with the active PCB layers of the sub-stack.

[0041] The digital sub-stack 3 includes a radar control circuit 22, a digital signal processor (DRSP) 23, a radio frequency (RF) distributor 24, a reference signal generator 25 and a power distribution unit (PDU) 26. Between the radar control circuit 22 and the digital signal processor (DRSP) 23 a relevant liquid-cooled cooling plate 27 is inserted, in thermal exchange contact with the active PCB layers of the sub-stack.

[0042] The PCB layers of the analog and digital sub-stacks 2, 3 are electrically connected together, as needed, by multipolar connectors (not shown), all located on one edge of the PCB layers of the stack, preferably arranged on the lower side 15.

[0043] The layers forming the analog and digital sub-stacks 2, 3 are hold together in close proximity or contact by mechanical connectors 28, such as pins, screws or the like, and supports 29, and the whole assembly is housed in an enclosure 30, which preferably corresponds in shape to the outline of the stacks and comprises a front wall 31 bearing relevant electrical connectors 33 for power and signals supply and the hydraulic connectors 35 (such as "quick-lock" connectors) for cooling fluid supply to the fluid-cooled cooling plates 20, 27. The enclosure 30 is essentially closed to the outside environment, being air and water tight.

[0044] The functional layers (i.e. the layers forming the analog and digital sub-stacks 2, 3) have an essentially 2D planar shape (i.e. each layer has components arranged substantially in a plane and the layers are electrically connected with each other only by connecting elements 15 arranged on one side, such as the lower side 16).

[0045] In turn, the cooling plates 20, 27 have a substantially planar shape, such that they do not extend transversally to the layers they are adjacent to.

[0046] This arrangement is such that the functional layers and the cooling plates are not overlapping in the 3D space (i.e. transversally to the surface of the layers). This enables any of the functional layers and cooling plates to be pulled out of the stack, upon removal of some of the mechanical connectors 28, as needed, without requiring dismantling of the whole stack assembly, thereby simplifying and accelerating maintenance and repair activities.

[0047] To this purpose, cooling plates 20, 27 and the PCB layers of the stacks 2, 3 have cutouts 17, located on their lower edges, open toward the outer edge of the relevant cooling plate and PCB layer, around the hydraulic and electric connection elements, enabling cooling plates 20, 27 and the PCB layers to be pulled out, for example along the direction P shown in figure 1, without disconnection of the adjacent elements.

[0048] The cooling plate 20 for the analog sub-stack 2 is shown in figure 4. The cooling plate 20 is a substantially flat plate, wherein channels 40 are formed, according to a path defined by the cooling needs of the chipsets in the facing portions of the analog sub-stack 2.

[0049] Inlet and outlet ports 41, 42 enable cooling fluid from the hydraulic connectors 35 to be supplied to the channels

40.

[0050] In turn, the cooling plate 27 for the digital sub-stack 3 is shown in figure 5, and includes relevant channels 44 and inlet and outlet ports 45, 46 suitably connected to the hydraulic connectors 35.

[0051] Preferably, the volume of the cooling fluid path of the cooling plate 27 of the digital sub-stack 3 is lower than the volume of the cooling fluid path of the analog cooling plate 20 of the analog sub-stack 2.

[0052] Consequently, the retention time for the cooling fluid in the cooling plate 20 of the analog sub-stack 2 is higher than in the cooling plate 27 of the digital sub-stack 3, allowing a greater amount of heat to be transferred to the cooling fluid. This could be convenient in view of the higher amount of heat generated in the analog sub-stack compared with the digital one, and the relevant heat absorption capability needs.

[0053] The heat transporting agent, i.e. the cooling fluid, can be water. In the following, unless otherwise specified, the term "water" is meant to encompass either pure water or a mixture of water with one or more additives, to be selected according to the needs of the specific field of use, temperature range and the like. For example, a preferred cooling fluid is a mixture made of about 37% water and 67% glycol.

[0054] The cooling plate 20 of the analog sub-stack 2 and the cooling plate 27 of the digital sub-stack 3 can either be connected together either in series, as shown in figures 6, 7, or in parallel, as shown in figures 8, 9.

[0055] In both cases, as schematically shown in figure 3, the cooling fluid coming from a heat sink 50 is supplied to the hydraulic connectors 35 and to the inlet ports of the cooling plates 20, 27, preferably with the aid of a pump 51, through cooling fluid transferring means such as piping 52 (schematically shown).

[0056] In the heat sink 50 the heat of the cooling fluid is removed to the ambient air. The heat sink can be a traditional radiator grill, which can be exposed to ambient air and can comprise additional fans to increase the flow of ambient air through the grill. Alternatively, or additionally a chiller can be coupled to the heat sink wherein the chiller cools the water actively.

[0057] In operation, in case of serial connection of the cooling plates as shown in figure 7, the cooling fluid is first supplied inside the analog cooling plate 20 through the relevant inlet port 41, streams through the multitude of water paths or channels 40 and exits through the outlet port 42. During this transition, the cooling fluid absorbs the heat from the adjacent functional layers of the analog cooling plate. The warm cooling fluid exits the analog cooling plate at the outlet port 42 and flows through a cooling fluid transferring means such as a pipe 47 or the like, to the inlet port 45 of the digital cooling plate 27.

[0058] From the inlet port 45 the cooling fluid then flows through the fluid paths or channels 44 of the digital cooling plate 27 to its outlet port 46, absorbing the relevant generated heat and finally to the relevant hydraulic connector 35 and to the heat sink 50, where it is cooled and circulated again.

[0059] In case of parallel connection of the analog and digital cooling plates 20, 27, as shown in figures 8, 9, the cooling fluid supplied to the hydraulic connector 35 enters both the inlet port 41 of the analog cooling plate 20 and the inlet port 45 of the digital cooling plate 27, streams through the multitude of water paths or channels 40, 44 and exits through the outlet ports 42, 46.

[0060] Inlet ports 41, 45 are connected to the relevant hydraulic connector 35 via a cooling fluid transferring means such as a pipe 48 or the like and conversely the outlet ports 42, 46 are connected to the relevant hydraulic connector 35 via a cooling fluid transferring means such as a pipe 49.

[0061] As shown in fig. 10, a plurality of radar systems can be hydraulically connected via the relevant piping system 52 to a single chiller or heat sink 50, with relevant flows of the cooling fluid controlled by liquid distributors 53 and valve systems 54.

[0062] Generally, the power consumption and the excess heat production of the analog sub-stack exceeds the same values of the digital layer by several factors. This factor can be as much as 2:1, 3:1 or even 4:1 or higher depending on the current radar operation mode. While the digital sub-stack usually shows a constant power draw, the power draw of the analog sub-stack varies substantially with the chosen operation mode of the radar (high power / low power; close range / long range etc.).

[0063] Depending on the size of the radar system the digital sub-stack can have a power draw in the range of from 100W to up to 500W- The analog sub-stack can show a power draw from 300W to up to 1500W.

[0064] In a particular preferred embodiment of the present invention the digital sub-stack has a power draw of about 200W and the analog sub-stack has a power draw of about 600W.

Example

[0065] An analysis was made by considering in detail components power dissipation and thermal local distribution for a radar system comprising components arranged in stacked layers.

[0066] The power dissipation of an exemplary radar system has been considered.

Item	Generated power	Analog/Digital
ARX	70W	A
EPC	140W	A
SSPA	385W	A
Clock distributor	5W	D
RF distributor	8W	D
PDU	10W	D
Radar Controller	60W	D
DRSP	180W	D

[0067] The total generated power was 858W, of which 595W in the analog sub-rack and 263W in the digital sub-rack.

[0068] Liquid cooling was considered for power dissipation, implementing two cooling plates respectively for the digital and analogical components.

[0069] The cooling fluid was 37% water and 67% glycol, provided by a dedicated chiller at 25°C.

[0070] A dedicated thermal model has been used to perform dedicated analyses.

[0071] Two main layouts have been considered, wherein the digital and analogical cooling plates were connected in parallel or in series for the liquid passage, respectively. For the series layout, different cases have been analyzed, changing some design parameters (such as "quick-lock" connector types and different liquid channels layout, selected by opening/closing some of the channels 40 of the relevant cooling plate).

[0072] Temperatures on both digital and analogical cooling plates and main components (cards/carter) have been calculated, as well as fluid temperature and other design values.

[0073] The following table summarizes some of the temperatures (in °C) obtained with the different architectures. V01 was a parallel design, and V02 to V05 were series designs, with different hydraulic connectors types and different liquid channels layout in the cooling plates, resulting in different pressure drop. In all examples, total cooling fluid flow rate was 2.5 l/min. Internal channels of the cooling plates had 6 mm diameter.

Description	V01	V02	V03	V04	V05
Ave. Temp. Radar Controller Interface	32.8	36.6	36.6	35.0	35.1
Ave. Temp. Carter DRSP Interface	33.1	37.0	37.0	35.4	35.5
Ave. Temp. Carter ARX Interface	59.8	44.1	44.7	41.0	41.1
Ave. Temp. Digital Cooling Plate Radar Controller Side	32.5	36.3	36.1	34.6	34.8
Ave. Temp. Digital Cooling Plate DRSP Side	32.6	36.4	36.2	34.7	34.8
Ave. Temp. Analog Cooling Plate EPC Side	54.6	39.3	40.0	36.0	36.2
Ave. Temp. Analog Cooling Plate SSPA Side	54.6	39.4	39.9	36.1	36.4
Outlet Liquid Temperature Analogical Cooling Plate	45.0	29.3	29.3	29.3	29.3
Outlet Liquid Temperature Digital Cooling Plate	27.4	31.1	31.1	31.1	31.1
Outlet Liquid Temperature	31.1	31.1	31.1	31.1	31.1

[0074] Analyses showed positive results in terms of cooling plates and carter interface tem peratures.

[0075] The series configurations gave better results in terms of temperature uniformity among the components.

[0076] In case different cooling fluids are required, for example for applications in particular environments, the fluid channels paths, relevant flow rates, pressure drops and so on should be designed specifically.

Claims

1. A radar system comprising a stack of functional printed circuit boards arranged in layers, housed in a common enclosure (30), **characterized in that** the stack of functional printed circuit boards layers comprises at least two sub-stacks (2, 3) and at least two cooling plates (20, 27), wherein each of the cooling plates (20, 27) is in thermal contact with one of the sub-stacks (2, 3), and wherein at least two cooling plates (20, 27) are thermally connected with each other by cooling fluid transferring means (47, 48, 49) and are connected to a heat sink (50) external to the common enclosure (31), wherein the stack of functional layers comprises an analog sub-stack (2) and a digital sub-stack (3) and the cooling plates comprise an analog cooling plate (20) and a digital cooling plate (27), in thermal contact with the analog sub-stack (2) and the digital sub-stack (3) respectively, and wherein the analog sub-stack comprises at least an analog receiver (6), an electrical power controller (7), a solid-state power amplifier (8), and an antenna (11).

2. A radar system comprising a stack of functional printed circuit boards arranged in layers, housed in a common enclosure (30), **characterized in that** the stack of functional printed circuit boards layers comprises at least two sub-stacks (2, 3) and at least two cooling plates (20, 27), wherein each of the cooling plates (20, 27) is in thermal contact with one of the sub-stacks (2, 3), and wherein at least two cooling plates (20, 27) are thermally connected with each other by cooling fluid transferring means (47, 48, 49) and are connected to a heat sink (50) external to the common enclosure (31), wherein the stack of functional layers comprises an analog sub-stack (2) and a digital sub-stack (3) and the cooling plates comprise an analog cooling plate (20) and a digital cooling plate (27), in thermal contact with the analog sub-stack (2) and the digital sub-stack (3) respectively, and wherein the analog cooling plate (20) and the digital cooling plate (27) are hydraulically connected in series.

3. A radar system according to claim 1, **characterized in that** the cooling fluid transferring means (47, 48, 49) connecting the cooling plates are arranged within the external outline of the stack of functional layers.

4. A radar system according to claim 1, **characterized in that** the digital sub-stack comprises at least a radar control circuit (22), a digital signal processor (23), a radio frequency distributor (24), a reference signal generator (25) and a power distribution unit (26).

5. A radar system according to claim 1, **characterized in that** the common enclosure (30) is air and water tight.

6. A radar system according to claim 1, **characterized in that** at least one of the functional printed circuit boards comprises electrical connectors arranged on one side only of the board whereby the board is capable of being dismantled from the stack independently of the adjacent boards.

7. A radar system according to claim 6, **characterized in that** at least one of the functional printed circuit boards comprises an open cutout (17), around a cooling fluid transferring means (47, 48, 49) and/or an electric connecting element (15).

8. A method of cooling a radar system comprising the steps of:

   - arranging the active components of the radar system in one or more functional printed circuit boards layers arranged in a stack within a common enclosure;
   - grouping the functional layers of the stack in at least a first sub-stack comprising functional elements of analog type and a second sub-stack comprising functional elements of digital type,
   - providing at least a first and a second cooling plate, wherein said first cooling plate is in thermal exchange contact with at least one of the functional layers of the first sub-stack and wherein said second cooling plate is in thermal exchange contact with at least another one of the functional layers of the second sub-stack,
   - removing heat from one or more functional layers of the first sub-stack by said first cooling plate with a cooling fluid;
   - removing heat from one or more functional layers of the second sub-stack by said second cooling plate with a cooling fluid, and
   - connecting said first and second cooling plates to a heat sink external to the common enclosure;
   - transporting heat from at least one of said first and second cooling plates to the heat sink.

9. A method of cooling a radar system according to claim 8, **characterized in that** it comprises flowing the cooling fluid through said first and second cooling plates.

10. A method of cooling a radar system according to claim 9, **characterized in that** it comprises flowing the cooling fluid first through the cooling plate contacting the sub-stack grouping analog type functional elements and then through the cooling plate contacting the sub-stack grouping digital type functional elements.

11. A method of cooling a radar system according to claim 9, **characterized in that** it comprises circulating the cooling fluid through said first and second cooling plates and through the external heat sink.

12. A method of cooling a radar system according to claim 8, **characterized in that** the cooling fluid is water.

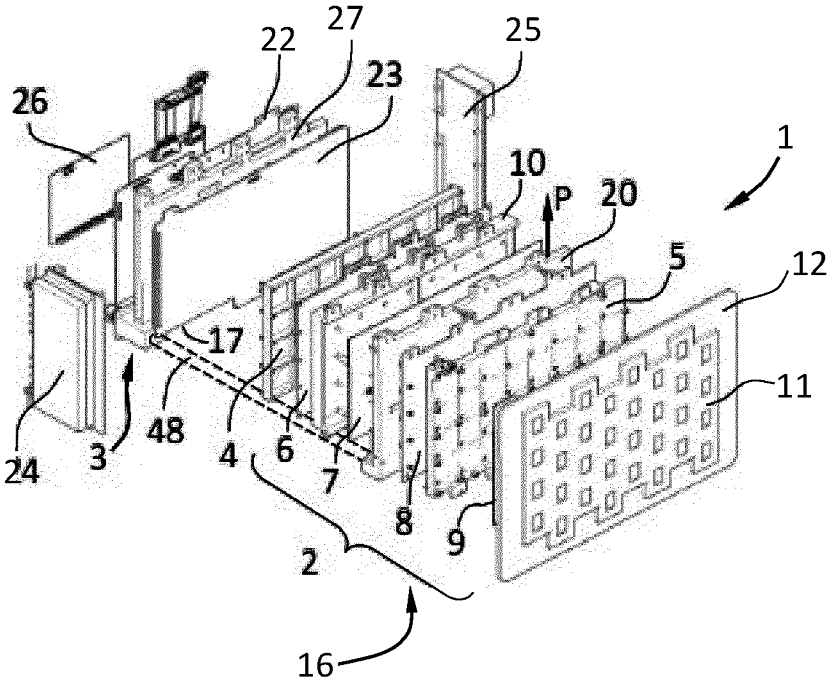
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Fig. 1

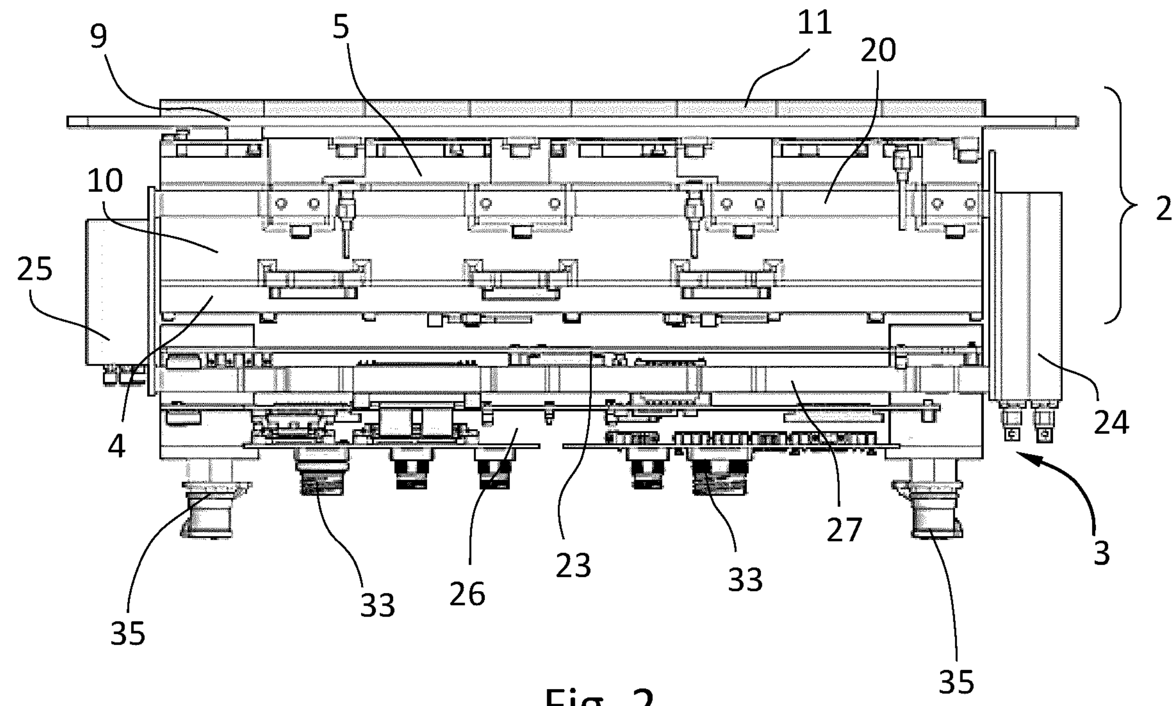
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Fig. 2

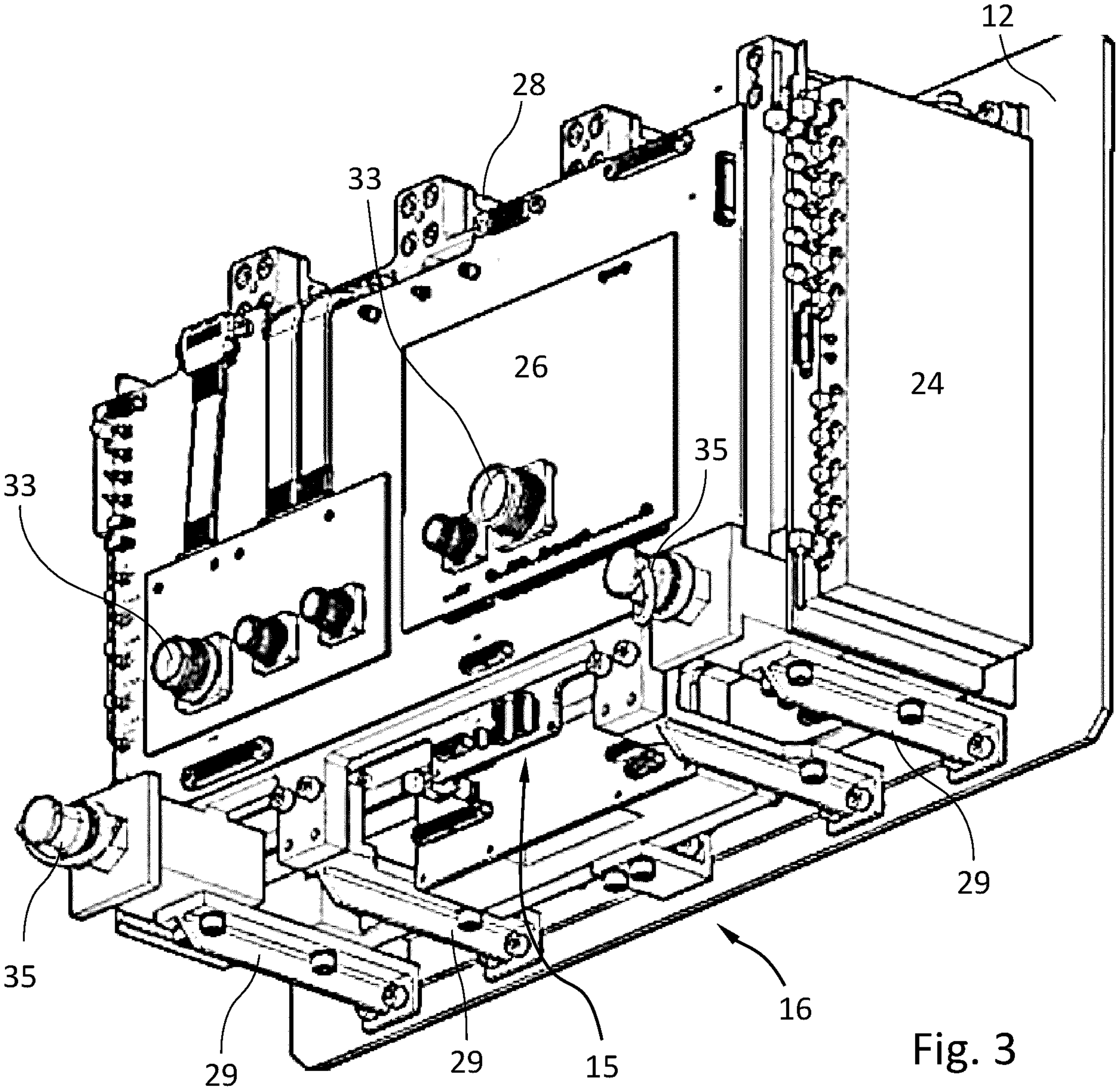

Fig. 3

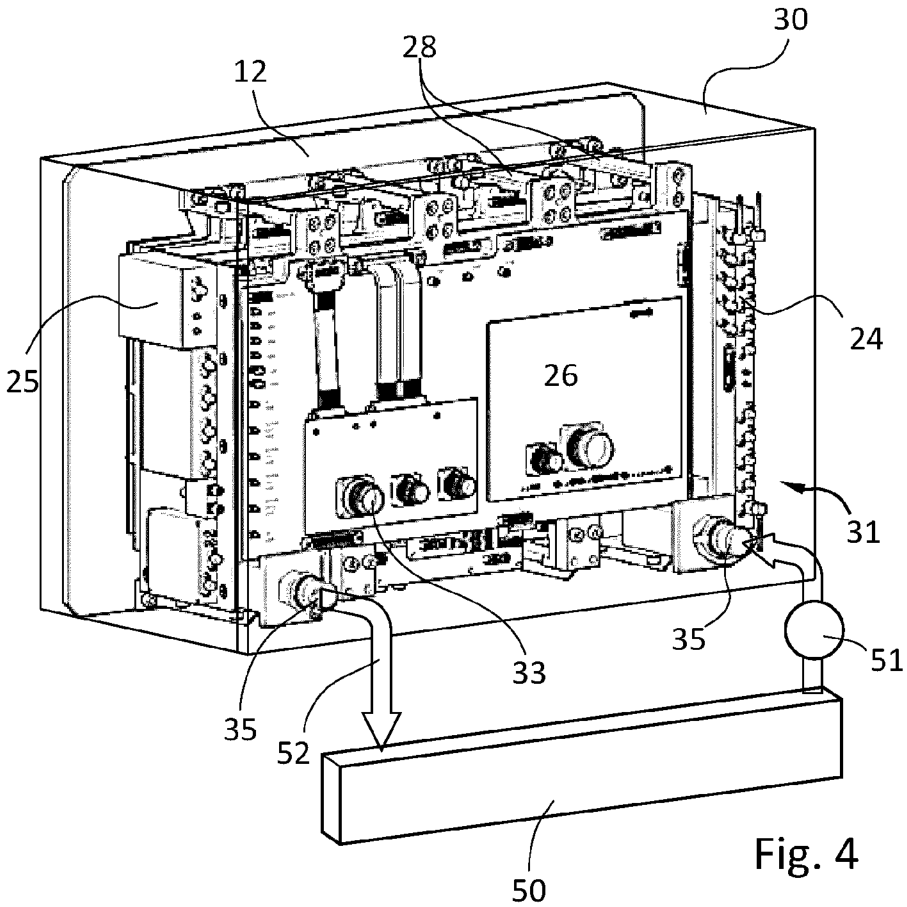

Fig. 4

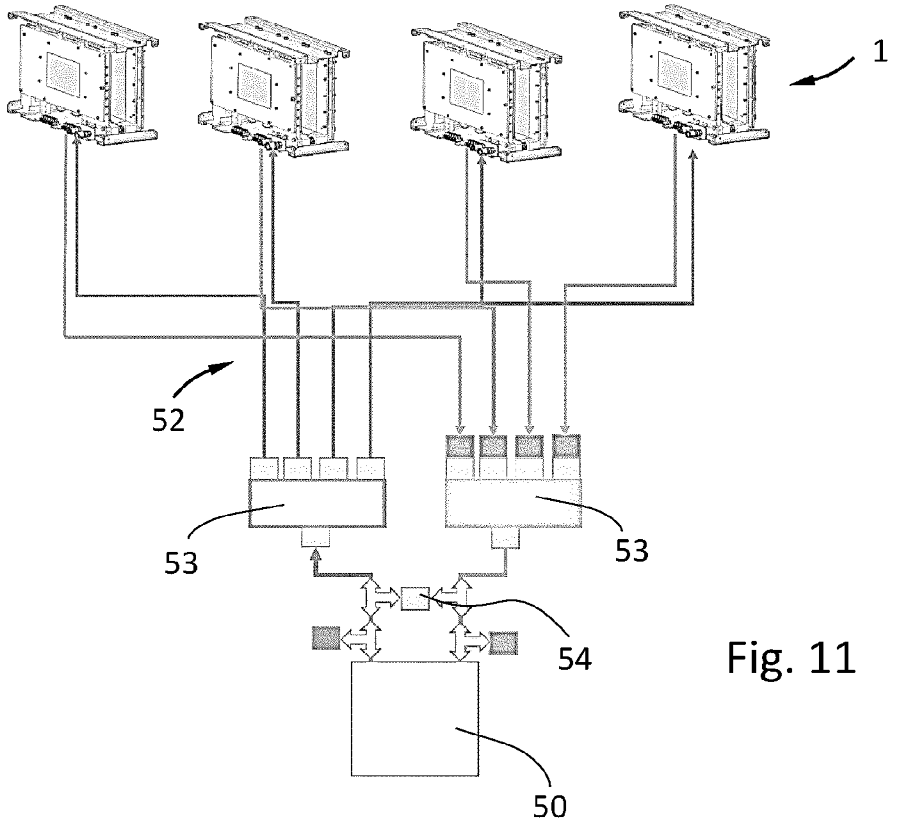

Fig. 11

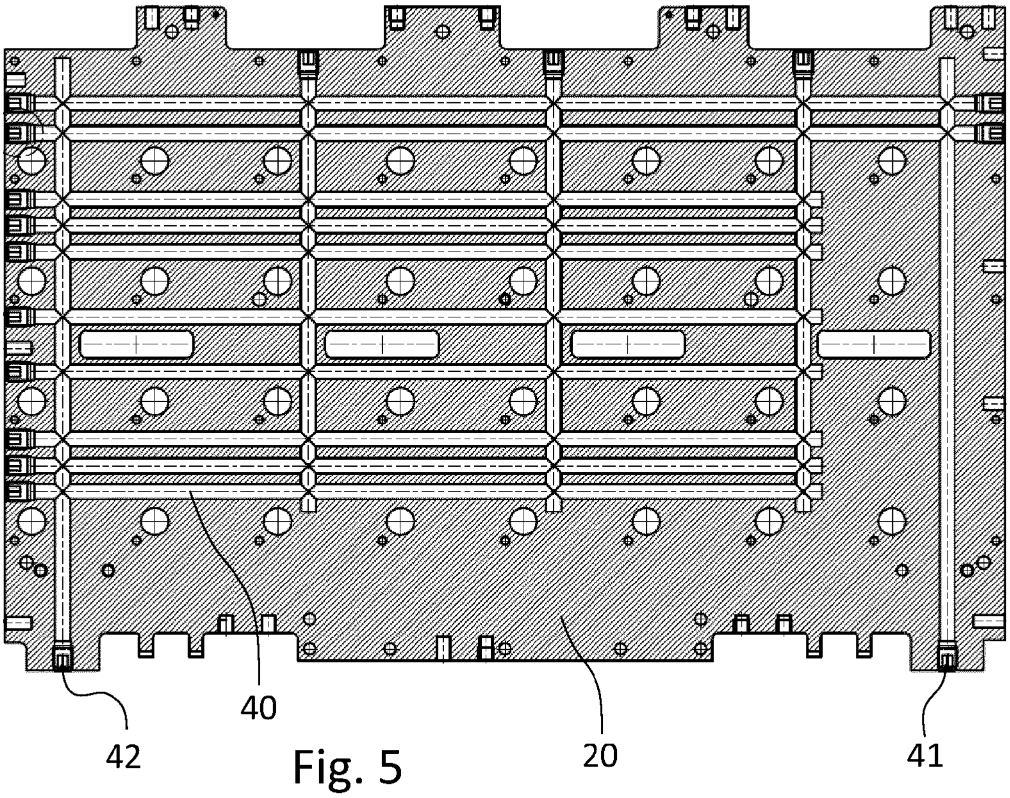

Fig. 5

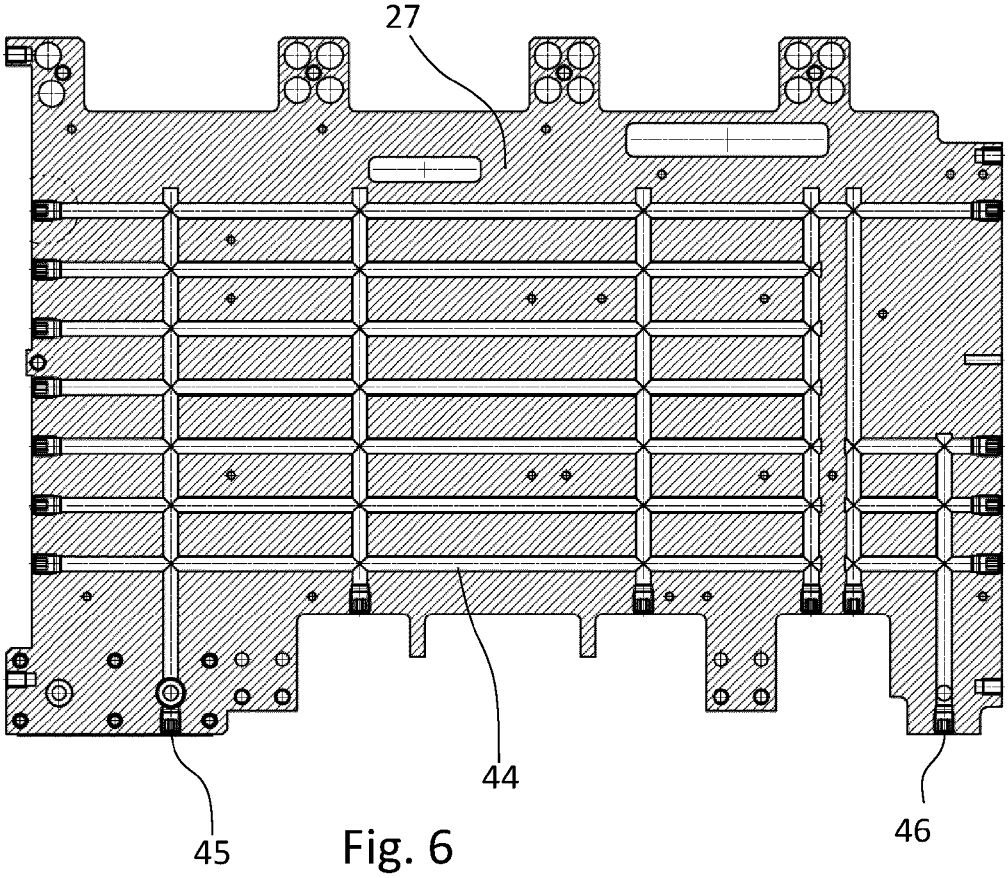

Fig. 6

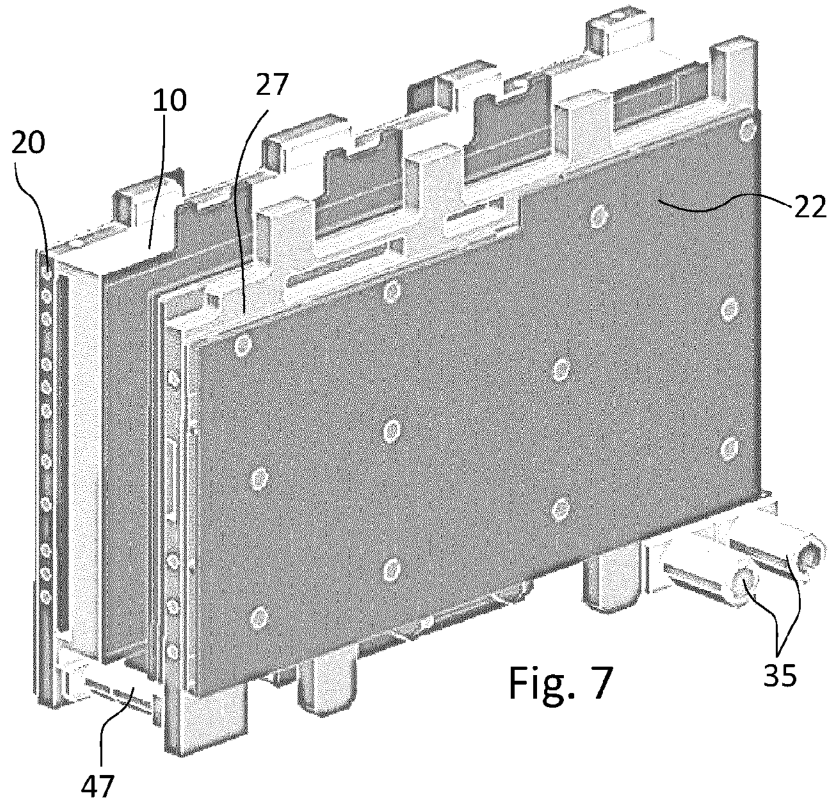

Fig. 7

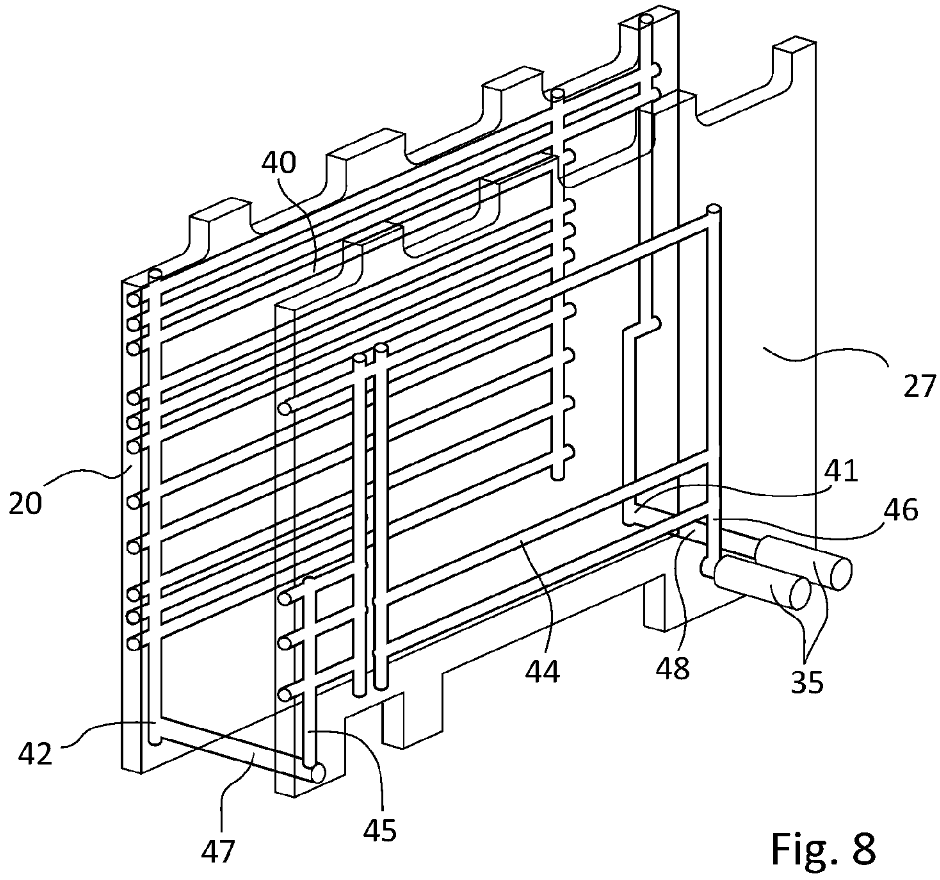

Fig. 8

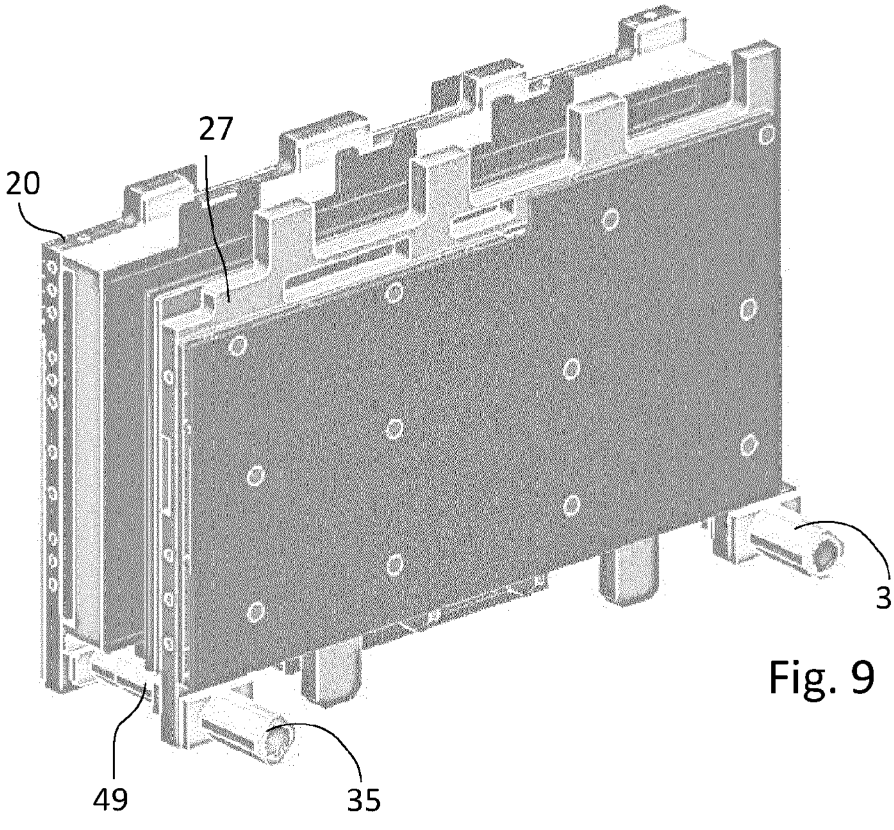

Fig. 9

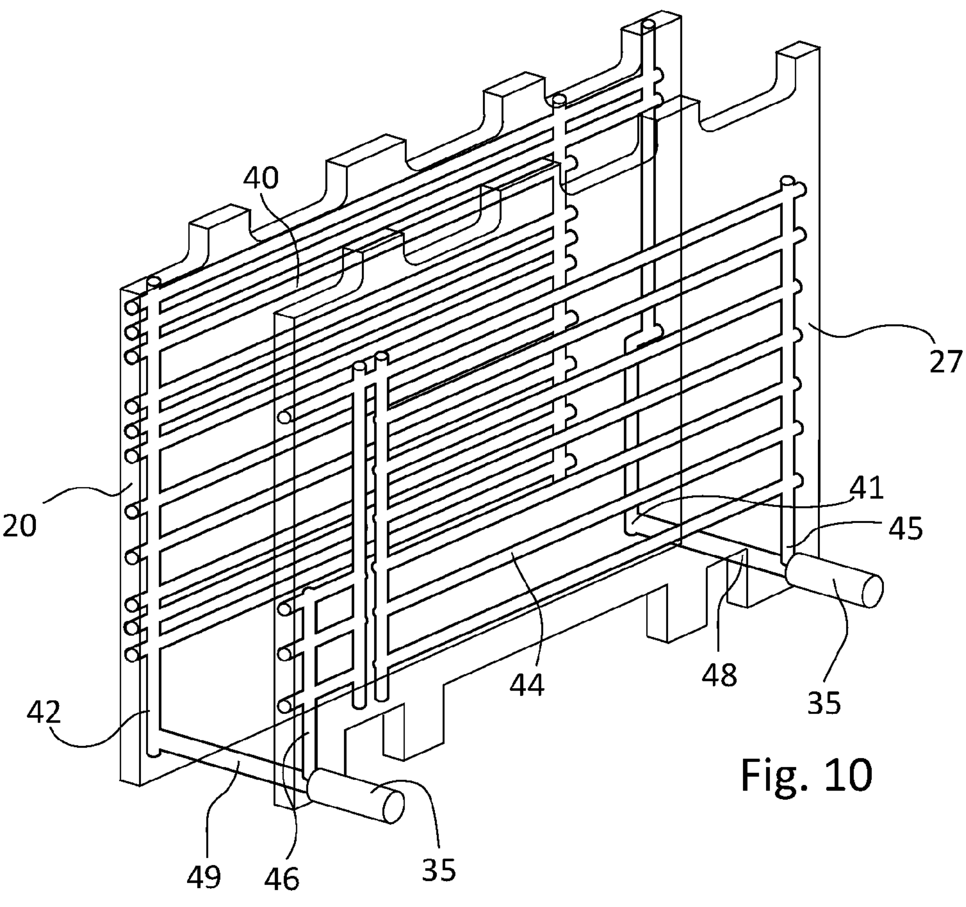

Fig. 10

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EUROPEAN SEARCH REPORT

Application Number
EP 23 21 9172

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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
The Hague	19 March 2024	Sípal, Vít

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