



(43) International Publication Date
6 September 2013 (06.09.2013)

- (51) International Patent Classification:
H01M 8/02 (2006.01) *H01M 8/04* (2006.01)
- (21) International Application Number:
PCT/CA2013/050143
- (22) International Filing Date:
26 February 2013 (26.02.2013)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:
61/603,734 27 February 2012 (27.02.2012) US
- (71) Applicant: **DANA CANADA CORPORATION**
[CA/CA]; 656 Kerr Street, Oakville, Ontario L6K 3E4 (CA).
- (72) Inventors: **VANDERWEES, Doug**; 1549 Tyandaga Court, Mississauga, Ontario L5H 3L4 (CA). **SHORE, Colin Arthur**; 402 East 36th, Hamilton, Ontario L8V 4A2 (CA).
- (74) Agent: **RIDOUT AND MAYBEE LLP**; 250 University Avenue, 5th Floor, Toronto, Ontario M5H 3E5 (CA).

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

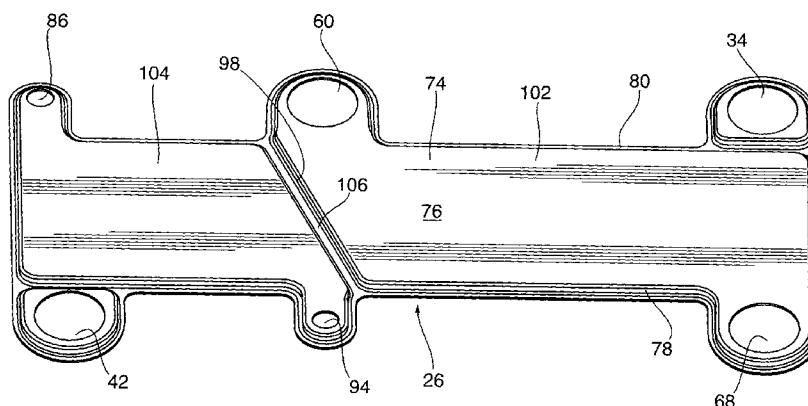
(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

(54) Title: METHOD AND SYSTEM FOR COOLING CHARGE AIR FOR A FUEL CELL, AND THREE-FLUID CHARGE AIR COOLER

Fig.6



(57) Abstract: A method and system for cooling a pressurized charge air in the fuel cell system of a vehicle, using first and second charge air coolers. The system further includes a gas-to-gas humidifier and a fuel cell stack. According to the method and system, cathode exhaust gas passes through the gas-to-gas humidifier and is also used as the coolant gas in the first charge-air cooler. Therefore, the fuel cell cathode exhaust is heated and reduced in water content, reducing the tendency of water in the exhaust to condense and pool underneath the vehicle. Also provided is a three-fluid heat exchanger which integrates the first and second charge air coolers.

METHOD AND SYSTEM FOR COOLING CHARGE AIR FOR A FUEL CELL, AND THREE-FLUID CHARGE AIR COOLER

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims priority to and the benefit of United States Provisional Patent Application No. 61/603,734 filed February 27, 2012, the contents of which are incorporated herein by reference.

FIELD OF THE INVENTION

[0002] The invention relates to methods and systems for cathode thermal management of fuel cell systems for vehicles, and to three-fluid charge air coolers which may be used in such methods and systems, but which are adapted for use in other systems where gas cooling is required.

BACKGROUND OF THE INVENTION

[0003] The cathode of a fuel cell utilizes pressurized charge air which is brought up to the fuel cell's operating pressure by an air compressor. During compression the air can become heated to a temperature of about 200° C or higher, which is considerably higher than the operating temperature of the fuel cell. Therefore, a charge air cooler is used to cool the pressurized charge air to the desired temperature before it reaches the fuel cell stack; and before it reaches a humidifier that may be in-line between the air compressor and the fuel cell stack.

[0004] Conventional cathode thermal management systems use a liquid-to-air charge air cooler to remove heat from the charge air. The liquid coolant is typically water or a water-glycol mixture which is circulated through the fuel cell cooling

- 2 -

system. The heat absorbed by the liquid coolant is subsequently rejected to the atmosphere through a heat exchanger, such as a radiator, in the front of the vehicle. The fuel cell engine itself also generates waste heat, which is low grade heat because of the relatively low stack operating temperature. This low grade heat rejection typically requires a relatively large radiator, and the added heat load from the charge air cooler that is rejected through this same radiator, forces a further increase in radiator size, to the point that the radiator may be difficult to package in the front space of the vehicle. Thus, the cooling of charge air places an additional load on the fuel cell's cooling system and complicates packaging in an already limited space. An example of such a prior art cathode thermal management system is illustrated in Figure 1A.

[0005] Alternative approaches to cathode thermal management are needed in order to reduce the thermal load on the fuel cell cooling system, while ensuring that the charge air is cooled to an appropriate temperature. Furthermore, it is desired to reduce parasitic energy losses in the cooling of fuel cell engine.

SUMMARY OF THE INVENTION

[0006] In one aspect there is provided a method for cooling a pressurized cathode air stream in a fuel cell system comprising a fuel cell stack, a first charge air cooler comprising a gas-to-gas charge air cooler, a gas-to-gas humidifier, and a second charge air cooler. The method comprises: (a) providing said pressurized cathode air stream having a first temperature (T_1); (b) passing said pressurized cathode air stream through said first charge air cooler in heat exchange with a cathode exhaust gas stream from said fuel cell stack, wherein said cathode exhaust gas stream has a second temperature (T_2) at an inlet of said first charge air cooler and said pressurized cathode air stream is cooled to a third temperature (T_3) at an outlet of said first charge air cooler; (c) passing said pressurized cathode air stream

through said second charge air cooler in heat exchange with a liquid or gaseous coolant having a fourth temperature (T_4) at a coolant inlet of said liquid-to-gas charge air cooler, wherein said pressurized cathode air stream is cooled to a fifth temperature (T_5) at an outlet of said second charge air cooler; (d) passing said pressurized cathode air stream and said cathode exhaust stream through said gas-to-gas humidifier, wherein water vapour is transferred from the cathode exhaust stream to the pressurized cathode air stream in said humidifier; and (e) passing said pressurized cathode air stream to a cathode air inlet of said fuel cell stack. The cathode exhaust stream passes through said gas-to-gas humidifier before passing through said first charge air cooler; and wherein said pressurized cathode air stream passes through said humidifier after it passes through said second charge air cooler and before it enters the cathode air inlet of said fuel cell stack.

[0007] In an embodiment, temperatures $T_2 < T_3 < T_1$ and/or $T_4 < T_5 < T_3$ under normal operating conditions.

[0008] In an embodiment, the cathode exhaust gas stream is at a sixth temperature (T_6) at an inlet of said gas-to-gas humidifier and wherein the pressurized cathode air stream is at a seventh temperature (T_7) at an outlet of the gas-to-gas humidifier, wherein $T_5 < T_7 < T_6$ under normal operating conditions. Also, in some embodiments, $T_2 < T_6$ under normal operating conditions.

[0009] In an embodiment, the second charge air cooler is a liquid-to-gas charge air cooler and wherein the liquid coolant absorbs heat from one or more other heat sources within the fuel cell system.

[0010] In an embodiment, the amount of thermal energy removed from the pressurized cathode air stream by the first charge air cooler is greater than the

amount of thermal energy removed from the pressurized cathode air stream by the second charge air cooler.

[0011] In another aspect, there is provided a system for producing a pressurized cathode air stream for use in a fuel cell. The system comprises: (a) a first charge air cooler comprising a gas-to-gas charge air cooler for cooling said pressurized cathode air stream from a first temperature (T_1) to a third temperature (T_3) with a gaseous coolant having a second temperature (T_2) at an inlet of the first charge air cooler; (b) a second charge air cooler for cooling said pressurized cathode air stream from T_3 to a fifth temperature (T_5) with a liquid or gaseous coolant having a fourth temperature (T_4) at a coolant inlet of said second charge air cooler; (c) a gas-to-gas humidifier for increasing a water content of the pressurized cathode air stream by transfer of water from a humidifying gas; and (d) a fuel cell stack having a cathode air inlet and a cathode exhaust gas outlet. The humidifying gas comprises a cathode exhaust gas stream from the cathode exhaust gas outlet of the fuel cell stack. The gaseous coolant of the first charge air cooler comprises the cathode exhaust gas stream. The first charge air cooler is arranged to receive the cathode exhaust gas stream from the humidifier and the humidifier is arranged to receive the cathode exhaust gas stream from the cathode exhaust gas outlet of the fuel cell stack.

[0012] In an embodiment, the first charge air cooler and the second charge air cooler are arranged sequentially such that the second charge air cooler receives said pressurized cathode air stream at said third temperature (T_3) from said first charge air cooler.

[0013] In an embodiment, the second charge air cooler is a liquid-to-gas charge air cooler, and wherein the first charge air cooler and the second charge air cooler are integrated into a three-fluid charge air cooler comprising a plurality of

flow passages for said pressurized cathode air stream, a plurality of flow passages for said gaseous coolant, and a plurality of flow passages for said liquid coolant.

[0014] In an embodiment, the cathode air inlet receives said pressurized cathode air stream from said gas-to-gas humidifier, which may be a membrane humidifier.

[0015] In an embodiment, the system further comprises a compressor which receives air at ambient temperature and pressure and compresses said ambient air to produce said pressurized cathode air stream at said first temperature (T_1), and wherein the first charge air cooler receives the pressurized cathode air stream from the compressor.

[0016] In an embodiment, the second charge air cooler is a gas-to-gas charge air cooler, wherein the second charge air cooler is cooled by a variable speed fan, and wherein the variable speed fan is controlled by a control circuit so as to maintain the temperature T_7 within a desired range.

[0017] In an embodiment, the second charge air cooler is a liquid-to-gas charge air cooler in which the pressurized cathode air stream is cooled by a liquid coolant which circulates through a cooling circuit which also includes the fuel cell stack, and wherein the cooling circuit includes a variable speed pump which controls the flow of the liquid coolant through the fuel cell stack and the second charge air cooler.

[0018] In yet another aspect there is provided a three-fluid charge air cooler. The charge air cooler comprises a plurality of plates arranged in a plate stack having a first end and a second end and a length extending from the first end to the second end, the plate stack being divided along its length into a first portion and a second

portion, the charge air cooler having a plurality of charge air flow passages alternating throughout the stack with a plurality of first coolant flow passages and with a plurality of second coolant flow passages. The three-fluid charge air cooler further comprises: a charge air inlet manifold and a charge air outlet manifold in flow communication with the plurality of charge air flow passages, wherein the charge air inlet manifold and the charge air outlet manifold are located proximate to opposite ends of the plate stack; a first coolant inlet manifold and a first coolant outlet manifold in flow communication with the plurality of said first coolant flow passages, wherein the first coolant flow passages extend along the second portion of the plate stack, wherein, the first coolant inlet manifold is located at the second end of the plate stack, and the first coolant outlet manifold is located in the second portion of the plate stack, proximate to said ribs; a second coolant inlet manifold and a second coolant outlet manifold in flow communication with the plurality of said second coolant flow passages, wherein the second coolant flow passages extend along the first portion of the plate stack, and wherein the second coolant inlet manifold is located in the first portion of the plate stack, proximate to said ribs, and the second coolant outlet manifold is located at the first end of the plate stack.

[0019] In an embodiment, the inlet and outlet manifolds for the charge air, the first coolant and the second coolant are integrally formed with and enclosed by the plate stack, and the charge air flow passages may extend along the entire length of the plate stack. The three-fluid charge air cooler may further comprise a plurality of ribs dividing the first portion of the stack from the second portion, wherein each of the ribs is formed in one of the plates of the plate stack and extends transversely across said plate to separate one of the first coolant flow passages from one of the second coolant flow passages, such that the plurality of ribs separate the plurality of first coolant flow passages from the plurality of second coolant flow passages.

- 7 -

[0020] In an embodiment, the charge air inlet manifold is located at the first end of the plate stack and the charge air outlet manifold is located at the second end of the plate stack.

[0021] In an embodiment, the plate stack includes a plurality of first core plates and a plurality of second core plates, each of the first core plates and each of the second core plates having a flat plate bottom surrounded by an upstanding wall; wherein the flat plate bottom of each said first core plate is sealed to the flat plate bottom of an adjacent one of said second core plates, wherein pairs of first and second core plates sealed together along their plate bottoms are separated by flat separator plates. The flat plate bottom of at least one of the first and second core plates in each said pair of plates may be provided with at least one hole.

BRIEF DESCRIPTION OF THE DRAWINGS

[0022] Embodiments of the invention are now discussed below with reference to the drawings, in which:

[0023] Figure 1A is a schematic diagram illustrating a conventional method and system for cathode thermal management of a fuel cell system.

[0024] Figure 1B is a schematic diagram illustrating a method and system for cathode thermal management of a fuel cell system according to a first embodiment of the invention.

[0025] Figure 1C is a schematic diagram illustrating a method and system for cathode thermal management of a fuel cell system according to a second embodiment of the invention.

[0026] Figure 2 is a top perspective view of the core of a heat exchanger according to a first embodiment.

[0027] Figure 3 is a top perspective view of a first core plate thereof.

[0028] Figure 4 is a bottom perspective view of the first core plate.

[0029] Figure 5 is a top perspective view of a second core plate thereof.

[0030] Figure 6 is a bottom perspective view of the second core plate.

[0031] Figure 7 is a top perspective view of a separator plate.

[0032] Figure 8 is a top, front perspective view of the heat exchanger core of the first embodiment.

[0033] Figure 9 is a transverse cross section along line 9-9' of Figure 8.

[0034] Figure 10 is a transverse cross section along line 10-10' of Figure 8.

[0035] Figure 11 is a transverse cross section along line 11-11' of Figure 8.

[0036] Figure 12 is a top perspective view of the core of a heat exchanger according to a second embodiment.

[0037] Figure 13 is a top plan view of a first core plate thereof.

[0038] Figure 14 is a bottom perspective view of the first core plate.

[0039] Figure 15 is a top perspective view of a second core plate thereof.

- [0040]** Figure 16 is a bottom perspective view of the second core plate.
- [0041]** Figure 17 is a transverse cross section along line 17-17' of Figure 12.
- [0042]** Figure 18 is a transverse cross section along line 18-18' of Figure 12.
- [0043]** Figure 19 is a transverse cross section along line 19-19' of Figure 12.

DETAILED DESCRIPTION

[0044] The following is a description of the embodiments of the invention illustrated in the drawings.

[0045] A method and system for cooling and humidifying a pressurized cathode air stream in a fuel cell system are discussed below with reference to Figures 1B and 1C. The following description mentions specific temperatures of various fluid streams within a fuel cell system. It will be appreciated that any temperatures mentioned herein are for the purpose of illustration only, and do not limit the invention. Furthermore, the temperatures disclosed herein are illustrative of fluid temperatures under steady state or normal operating conditions, and there can be significant temperature variations under cold start or other transient conditions. Under normal operating conditions the power level in the fuel cell stack is not radically changing, and most of the exothermic heat generated by the stack is absorbed by the fuel cell's cooling system, with a small amount of the energy of the fuel cell being used to heat up the cathode stream to aid in the uptake of water on the cathode side of the stack.

[0046] Figures 1B and 1C each schematically illustrate a number of components of a vehicle having a fuel cell engine, especially an automotive fuel cell

engine system 10 that uses a pressurized and humidified cathode air supply; and in particular those components which relate to the supply of this air to the cathode of the fuel cell.

[0047] The illustrated system 10 comprises an air compressor 12 which receives air at ambient temperature and pressure and compresses the air to a pressure suitable for introduction into the fuel cell stack. The compression of the ambient air causes the temperature of the air to rise from ambient temperature to an elevated temperature, referred to herein as the first temperature T_1 . In a typical fuel cell system, the compression of ambient air in air compressor 12 produces compressed air having a temperature of about 200°C. The temperature T_1 is considerably higher than the operating temperature of the fuel cell (and the maximum tolerable temperature of the humidifier that may be located upstream of the fuel cell), and therefore the pressurized cathode air stream produced by the air compressor 12 must be cooled prior to its introduction into the humidifier and/or fuel cell stack.

[0048] The system further comprises a first charge air cooler 14, which is a gas-to-gas charge air cooler. The first charge air cooler 14 receives the pressurized cathode air stream from the air compressor 12. The first charge air cooler 14 includes a cathode air inlet which receives the pressurized cathode air stream at temperature T_1 , and a cathode air outlet which discharges the pressurized cathode air stream at a third temperature T_3 , wherein $T_3 < T_1$. The first charge air cooler 14 cools the pressurized cathode air stream from T_1 to T_3 with a gaseous coolant drawn from the fuel cell cathode exhaust and having a second temperature T_2 , wherein $T_2 < T_3 < T_1$ under steady state or normal operating conditions of the fuel cell system. There may be some variability in these relative temperatures under cold start and transient conditions.

- 11 -

[0049] The first charge air cooler 14 further comprises a coolant inlet to receive the gaseous coolant at temperature T_2 , and a coolant outlet to discharge the gaseous coolant from the first charge air cooler 14. In an embodiment of the invention, the temperature T_2 of the gaseous coolant is from about 90 to 100°C, for example about 94°C, and the gaseous coolant is heated by the pressurized cathode air stream to a temperature of about 175°C at the coolant outlet of the first charge air cooler 14. The heated gaseous coolant discharged from the first charge air cooler 14 may be released into the environment or used as a heat source elsewhere in the system 10.

[0050] The system 10 further comprises a second charge air cooler 16 for cooling the pressurized cathode air stream from temperature T_3 to a fifth temperature T_5 . The second charge air cooler 16 may be a second gas-to-gas charge air cooler, which may use a controlled, variable-speed fan to control temperature T_5 . Regardless of whether the second charge air cooler 16 uses a liquid or gaseous coolant, the coolant has a fourth temperature T_4 , wherein $T_4 < T_5 < T_3$ under steady state or normal operating conditions of the fuel cell system. There may be some variability in these relative temperatures under cold start and transient conditions. Under steady state or normal operating conditions, temperature T_5 may be from about 85 to 95°C, for example about 90°C. A variant of system 10 in which the second charge air cooler 16 uses a liquid coolant is described below with reference to Figure 1C.

[0051] The second charge air cooler 16 includes a cathode air inlet which receives the pressurized cathode air stream at temperature T_3 and a cathode air outlet which discharges the pressurized cathode air stream at temperature T_5 . The second charge air cooler 16 further comprises a coolant inlet which receives the gaseous or liquid coolant at temperature T_4 , and a coolant outlet which discharges the coolant from the second charge air cooler 16.

[0052] The second charge air cooler 16 performs a self-stabilizing function, in that it helps to ensure sufficient cooling under a greater range of operating conditions, particularly under certain transient conditions where cooling requirements are sharply increased. This self-stabilizing function ensures sufficient and consistent cooling of the charge air exiting the second charge air cooler 16. This is particularly important in view of the relatively low operating temperatures, and narrow range of operating temperatures, of the fuel cell stack and the membrane humidifier which may be located upstream of the fuel cell stack, both of which have typical average operating temperatures in the range from about 80 to 100° C. It will be appreciated, however, that there may not be any active control over the outlet temperature T_5 of the second charge air cooler 16. The relatively constant temperature T_6 of the cathode exhaust gas exiting fuel cell stack 20 protects the humidifier from overheating under transient conditions such as acceleration from a steady state (hot) condition with the stack 20 fully warmed, because T_6 is less than T_5 under such conditions.

[0053] Where the second charge air cooler 16 is air cooled, self-stabilization is achieved by providing the second charge air cooler 16 with a variable-speed fan (not shown), the operation of which is controlled by a control circuit which uses a thermistor or thermocouple to monitor the inlet temperature T_7 of the fuel cell stack 20 and/or the outlet temperature T_5 of the second charge air cooler 16.

[0054] Where the second charge air cooler 16 is cooled by water or a water/glycol coolant, self-stabilization is provided by the greater heat capacity of water. For example, as shown in Figure 1C, the second charge air cooler 16 and the fuel cell stack 20 may be included in a common cooling circuit 21 in which a variable speed pump 23 controls the coolant flow rate through the circuit 21, which includes the primary stack radiator 25 and a variable speed fan 27 provided at the primary stack radiator. The presence of the second charge air cooler 16, with the assistance

- 13 -

of the fan 27 and pump 23, help to stabilize the system and maintain the fuel cell stack inlet temperature T_7 at a consistent temperature under variable operating conditions or in the event of a malfunction of another component within the system 10. To ensure accurate temperature control of the fuel cell stack 20, the radiator 25 and fan 27 are shown in Figure 1C as being located upstream of the stack 20, and may for example be directly upstream of stack 20, such that the temperature of the liquid coolant exiting radiator 25 may be essentially the same as the temperature of the liquid coolant received by stack 20.

[0055] The stack inlet temperature T_7 may be actively controlled, eg. by sensors and control loops (not shown). The stack inlet and outlet temperatures T_7 and T_6 are measured by the sensors and the coolant flow in the common cooling circuit 21 is increased by increasing the speed of the pump 23 if T_6 is too high. This increases cooling at both the stack 20 and the second charge air cooler 16. Conversely, where T_7 is too low, the coolant flow in the circuit 21 is reduced by reducing the speed of pump 23, which simultaneously reduces cooling of both the stack 20 and the second charge air cooler 16.

[0056] The system 10 further comprises a gas-to-gas humidifier 18 for increasing the water content of the pressurized cathode air stream to a humidity level which is acceptable for introduction into the fuel cell stack. In an embodiment, the gas-to-gas humidifier 18 may comprise a membrane humidifier as described in U.S. Patent Application Publication No. US 2012/0181712 A1, which is incorporated herein by reference in its entirety.

[0057] The humidifier 18 includes a cathode air inlet for receiving the pressurized cathode air stream having a relatively low humidity level, and a cathode air outlet for discharging the pressurized cathode air stream at a relatively higher humidity level. The humidifier 18 further comprises a humidifying gas inlet to

- 14 -

receive a gas which contains water to be transferred to the pressurized cathode air stream, and a humidifying gas outlet for discharging the moisture-depleted humidifying gas from humidifier 18.

[0058] After the pressurized cathode air stream has been cooled and humidified, it flows to a fuel cell stack 20 having a cathode air inlet for receiving the pressurized cathode air stream, and a cathode exhaust gas outlet for discharging a cathode exhaust gas produced by chemical reactions taking place within the fuel cell stack. The fuel cell stack 20 may be considered a component of system 10, or may be considered a separate component of a fuel cell system.

[0059] The relatively large surface area of humidifier 18 makes it an effective heat exchanger, and its location immediately ahead of the fuel cell stack 12 helps to stabilize system 10 and maintain a consistent inlet temperature at the fuel cell stack 12 in the event of temperature spikes in the pressurized cathode air stream caused by transient conditions or a malfunction in the system 10. Thus, a second level of self-stabilization is provided by the humidifier 18, which relies on the relatively stable temperature T_6 of the cathode exhaust gas to deal with any transient temperature excursions in the pressurized cathode air system that survive the first level of stabilizing at the second charge air cooler 16.

[0060] In the embodiment shown in Figure 1, the first and second charge air coolers are arranged sequentially such that the second charge air cooler 16 receives the pressurized cathode air stream at temperature T_3 from the first charge air cooler 14. Locating the first charge air cooler 14 upstream (i.e. in the direction of flow of the pressurized cathode air stream) relative to the second charge air cooler 16 can be advantageous, particularly where the second charge air cooler 16 is a liquid-to-gas charge air cooler sharing coolant with other heat-producing components of the fuel cell system. Under normal operating conditions, most of the thermal energy

- 15 -

removed from the pressurized cathode air stream will be removed by the first charge air cooler 14, and a lesser amount of thermal energy is removed from the pressurized cathode air stream by the second charge air cooler 16. As a result, most of the waste heat from the charge air stream is rejected to the atmosphere rather than being absorbed by the fuel cell cooling system, at least under normal operating conditions. This can produce several benefits. For example, the use of the system and method of the present invention in a fuel cell system can help reduce thermal load on the fuel cell engine's cooling system, and may permit the use of a smaller radiator, saving space in the front end of the vehicle. At the same time, the cooling system can satisfy greater cooling demands of the cathode air stream under transient conditions. The system and method of the invention can also reduce parasitic energy losses in the cooling system of the fuel cell engine, such as losses due to operation of the radiator fan, by diverting more thermal load of the total system away from the liquid cooling system.

[0061] An additional benefit of the system and method of the invention, compared to standard practice, is that the fuel cell cathode exhaust is no longer discharged to atmosphere at approximately 80-90° C, a temperature low enough to cause water condensation and pooling of water or ice (in winter operation) underneath the vehicle. Instead, the system and method of the invention cause the fuel cell exhaust to be heated to a higher temperature after being used to cool the charge air stream. Exhausting the heated exhaust to ambient air at a higher temperature can avoid local condensation and water or ice pooling.

[0062] In an example, compression of the cathode air stream adds 14.5 kW of thermal energy into the cathode air stream, and about 10.5 kW of waste heat is removed from the compressed cathode air stream. The first charge air cooler removes about 10 kW of thermal energy and the second charge air cooler 16

removes about 0.5 kW of thermal energy. This is a reduction of about 10 kW of heat which would otherwise be rejected to the fuel cell liquid cooling system

[0063] Once it is cooled to temperature T_5 , the pressurized cathode air stream flows from the second charge air cooler 16 to the gas-to-gas humidifier 18.

[0064] The cathode exhaust gas stream exiting the fuel cell stack 20 typically has a temperature of about 90 to 100°C, which is slightly higher than the temperature of the pressurized cathode air stream entering the fuel cell stack 20. In addition, due to the production of water within the fuel cell stack, the moisture level of the cathode exhaust gas stream is relatively high. Accordingly, in the present invention, the humidifying gas flowing through the humidifier 18 comprises the cathode exhaust gas stream from the cathode exhaust gas outlet of the fuel cell stack 20. The removal of water from the fuel cell exhaust by the humidifier 18 also reduces the relative humidity of the exhaust.

[0065] There may also be a relatively small amount of heat exchange taking place in the humidifier 18. For example, as mentioned above, the temperature of the cathode exhaust gas exiting fuel cell stack 20 (represented by T_6 in Figure 1) is typically slightly higher than that of the pressurized cathode air stream (represented by T_7 in Figure 1) supplied to the fuel cell stack 20 from humidifier 18. In an embodiment of the invention, T_6 is about 95 to 100°C, for example about 96°C, whereas T_7 is typically from about 90 to 95°C, for example about 92°C, wherein $T_5 < T_7 < T_6$. Again, these are typical temperatures within the fuel cell system during steady state or normal operation, and may be different under cold start and transient conditions.

[0066] Thus, the cathode exhaust gas stream enters humidifier 18 at a slightly elevated temperature T_6 and is slightly cooled by the pressurized cathode air stream

- 17 -

entering humidifier 18 at temperature T_5 . As a result, the cathode exhaust gas stream may exit humidifier 18 at a slightly lower temperature T_2 than the temperature T_6 at the outlet of the fuel cell stack 20. It can be seen from the above discussion that the use of the cathode exhaust gas stream as a cooling and/or humidifying gas cools the pressurized cathode air stream to a temperature suitable for use in the fuel cell, and over-cooling or under-cooling of the cathode air stream can be avoided.

[0067] As shown in Figure 1, the cathode exhaust gas stream exits humidifier 18 at temperature T_2 and flows to the gas-to-gas charge air cooler 14 which may be located immediately downstream of the air compressor 12.

[0068] A method for cooling and humidifying a pressurized cathode air stream is now described below, in accordance with Figure 1.

[0069] As mentioned above, the fuel cell system may comprise the fuel cell stack 20, the first charge air cooler 14, the second charge air cooler 16, and the gas-to-gas humidifier 18.

[0070] According to the invention, a pressurized cathode air stream is provided at a temperature T_1 , for example from an air compressor 12. The pressurized cathode air stream is then passed through the gas-to-gas charge air cooler 14 and transfers heat to a cathode exhaust gas stream from the fuel cell stack 20. The cathode exhaust gas stream has a second temperature T_2 at an inlet of the first charge air cooler 14 and the pressurized cathode air stream is thereby cooled to a third temperature T_3 at an outlet of the first charge air cooler 14, wherein $T_2 < T_3 < T_1$ under steady state or normal operating conditions.

[0071] The pressurized cathode air stream is then passed through the second charge air cooler 16 and transfers heat to a gaseous or liquid coolant having a temperature T_4 at an inlet of the second charge air cooler 16. The pressurized cathode air stream is thereby cooled to a temperature T_5 at an outlet of the second charge air cooler 16, wherein $T_4 < T_5 < T_3$ under steady state or normal operating conditions.

[0072] The pressurized cathode air stream is then passed through the gas-to-gas humidifier 18, where the water content of the pressurized cathode air stream absorbs water from the cathode exhaust gas stream.

[0073] Once the pressurized cathode air stream has been cooled and humidified as described above, it is passed to a cathode air inlet of the fuel cell stack 20.

[0074] Having now described a system and method for cooling and humidifying a pressurized cathode air stream, the following is a description of three-fluid charge air coolers according to the invention, which integrate the first charge air cooler 14 and the second charge air cooler 16 schematically shown in Figure 1. Although the three-fluid charge air coolers described herein are adapted for use in the system and method according to the invention, they may be used in numerous other applications for cooling of a hot gas stream.

[0075] A three-fluid charge air cooler 100 according to a first embodiment of the invention is now described below with reference to Figures 2 to 11. The drawings illustrate a portion of the core 22 of heat exchanger 100. It will be appreciated that the heat exchanger 100 will also include other components such as a top plate, a bottom plate, a base plate for mounting heat exchanger 100 to another vehicle component, inlet and outlet fittings for the charge air and the

coolants, none of which are shown in the drawings. These components are conventional and their appearance and location may be at least partially dictated by space limitations. For example, the specific locations and configurations of the inlet and outlet openings and fittings for the charge air and the coolants depend on the specific configuration of the vehicle's air intake system and the fuel cell system, and will vary from one application to another.

[0076] The core 22 is "self-enclosed", meaning that the manifolds and flow passages are completely enclosed within the stack of plates from which core 22 is formed, and therefore the core 22 of heat exchanger 100 does not need to be enclosed within a separate housing.

[0077] The core 22 is made up of a plurality of plates which are joined together (for example by brazing) in order to form alternating flow passages for the charge air and the coolants. Core 22 includes a plurality of first core plates 24, a plurality of second core plates 26, and a plurality of flat separator plates 28.

[0078] The plates 24, 26, 28 and the core 22 are elongate, and define a longitudinal axis A shown in Figure 2. All of the plates and the core 22 include elongate sides which are at least generally parallel to axis A and relatively shorter ends which are transverse to axis A.

[0079] Heat exchanger 100 includes a charge air inlet manifold 30 which, in the illustrated embodiment, is located along a longitudinal side of core 22, adjacent to a corner, and is made up of aligned charge air inlet openings 32, 34 and 36 in respective plates 24, 26 and 28. The charge air inlet manifold 30 extends throughout the entire height of core 22. In the assembled heat exchanger 100, one end of charge air inlet manifold 30 will be blocked by a top or bottom plate and the other end of manifold 30 will receive hot, pressurized charge air from air

- 20 -

compressor 12 through an inlet fitting (not shown). It will be appreciated that the precise location, shape and appearance of the charge air inlet manifold 30 may vary from that shown in the drawings.

[0080] A charge air outlet manifold 38 is located along a side of core 22, adjacent to a corner. The charge air inlet manifold 30 and charge air outlet manifold 38 are located adjacent to opposite ends of the core 22 and, as shown, may be located at diagonally opposite corners of core 22. The charge air outlet manifold 38 is made up of aligned charge air outlet openings 40, 42 and 44 of respective core plates 24, 26 and 28. The charge air outlet manifold 38 extends throughout the entire height of core 22. One end of manifold 38 will be blocked by a top or bottom plate (not shown), and the opposite end will be provided with an outlet fitting (not shown) for discharging the cooled charge air to the gas-to-gas humidifier 18. The precise location, shape and appearance of the charge air outlet manifold 38 shown in the drawings is not essential. It is sufficient that the manifolds 30 and 38 are located at opposite ends of core 22, regardless of whether they are directly opposite or diagonally opposite to one another. For example, the inlet and outlet manifolds 30, 38 may be located along the same side of core 22, rather than at diagonally opposed corners, or they may be located at any point along the ends of the core 22.

[0081] The first core plate 24 has a top face 46 and a bottom face 48. Looking at top face 46, shown in Figure 2, plate 24 has a plate bottom 50 which is co-planar with the charge air inlet opening 32 and the charge air outlet opening 40 of plate 24. The plate bottom 50 and the outer periphery of plate 24 are surrounded by an upstanding wall 52 having a planar, upper sealing surface 54 for sealing to an adjacent plate. The upstanding wall 52 includes an outer peripheral portion which encloses the outer periphery of plate 24, and upstanding ribs which separate the coolant manifolds (described below) from the plate bottom 50. The

- 21 -

upper sealing surface 54 of plate 24 includes an outer peripheral flange which extends along the outer peripheral portion of upstanding wall 54, as well as planar sealing surfaces on the upstanding rib portions of upstanding wall 52. The pressurized charge air flows diagonally and longitudinally across the plate bottom 50 along the top face 46 of first core plate 24 from the charge air inlet opening 32 to the charge air outlet opening 40. Thus, a charge air flow passage 51 is defined along the rectangular area of the plate bottom 50.

[0082] The core 22 of heat exchanger 100 also includes a gaseous coolant inlet manifold 56 which is made up of gaseous coolant inlet openings 58, 60 and 62 of respective core plates 24, 26 and 28. The gaseous coolant inlet manifold 56 is located along a side of the core 22, partway between the ends, for reasons which will become apparent below. As with the charge air manifolds, the gaseous coolant inlet manifold 56 will be closed at one end by a top or bottom plate, and the opposite end of manifold 56 will be provided with an inlet fitting for receiving a gaseous coolant. For example, where the gaseous coolant is a cathode exhaust gas stream, the gaseous coolant inlet will be configured to receive the cathode exhaust gas stream either directly or indirectly from the fuel cell stack 20. It will be appreciated that the precise location and appearance of the gaseous coolant inlet manifold 56 may vary from that shown in the drawings.

[0083] The core 22 further comprises a gaseous coolant outlet manifold 64 which is made up of aligned gaseous coolant outlet openings 66, 68 and 70 of respective core plates 24, 26 and 28. The gaseous coolant outlet manifold 64 is located along a side of the core 22, proximate to one of the ends thereof. In the illustrated embodiment, the gaseous coolant outlet manifold 64 is located at a corner of the core 22, diagonally opposite from the gaseous coolant inlet manifold, although diagonal arrangement is not required. It will be appreciated that one end of the gaseous coolant outlet manifold 64 will be blocked by a top or bottom plate of

- 22 -

heat exchanger 100, and the opposite end of manifold 64 will be provided with an outlet fitting through which the gaseous coolant is discharged from the heat exchanger 100. The gaseous coolant, which is heated to an elevated temperature by heat exchange with the charge air, may either be discharged to the atmosphere or may be used elsewhere in the fuel cell system.

[0084] The second core plate 26 has a top face 72 and a bottom face 74. In the assembled core 22, the top face 72 of second core plate 26 is secured and sealed to the bottom face 48 of an adjacent first core plate 24 in the core 22, for example by brazing. Referring to Figure 5, the second core plate 26 has a plate bottom 76 which is co-planar with the gaseous coolant inlet opening 60 and the gaseous coolant outlet opening 68. The plate bottom 76 and the outer periphery of plate 26 are surrounded by an upstanding wall 78 provided with an upper, planar sealing surface 80 for sealing to an adjacent plate. The upstanding wall 78 includes an outer peripheral portion which encloses the outer periphery of plate 26, and upstanding ribs which separate the charge air manifolds 30 and 38 from the plate bottom 76. The upper sealing surface 80 of plate 26 includes an outer peripheral flange which extends along the outer peripheral portion of upstanding wall 78, as well as planar sealing surfaces on the upstanding rib portions of upstanding wall 78. It can be seen that the gaseous coolant will flow from the gaseous coolant inlet opening 60, diagonally along the plate bottom 76 on the bottom face 74 of plate 26, to the gaseous coolant outlet opening 68. In the illustrated embodiment, the gaseous coolant and the charge air flow in opposite directions along axis A.

[0085] The core 22 of heat exchanger 100 also includes a liquid coolant inlet manifold 82 which is made up of aligned liquid coolant inlet openings 84, 86 and 88 in respective core plates 24, 26 and 28. One end of the liquid coolant inlet manifold 82 will be blocked by a top or bottom plate, and the opposite end of manifold 82 will be provided with an inlet fitting for receiving the liquid coolant from a coolant

source. The liquid coolant inlet manifold 82 is located along a side of core 22, proximate to an end of core 22, and is shown in the drawings as being located at a corner of core 22. It will be appreciated that the precise location, shape and appearance of the liquid coolant inlet manifold 82 may vary from that shown in the drawings.

[0086] The core 22 also includes a liquid coolant outlet manifold 90 made up of aligned liquid coolant outlet openings 92, 94 and 96 of the respective core plates 24, 26 and 28. The liquid coolant outlet manifold 90 is located along a side of core 22, partway between the ends, and in the illustrated embodiment, is located directly across the core 22 from the gaseous coolant inlet manifold 56.

[0087] Referring again to the bottom face 74 of the second core plate 26 shown in Figure 5, it can be seen that the liquid coolant inlet opening 86 and the liquid coolant outlet opening 94 are co-planar with the plate bottom 76, and are also surrounded by the upstanding peripheral wall 78. Thus, the liquid coolant will flow from the liquid coolant inlet opening 94, along the plate bottom 76 on the bottom face 74 of second core plate 26, to the liquid coolant outlet opening 94. The liquid coolant therefore flows diagonally and longitudinally along the plate bottom 76, opposite the direction of flow of the charge air.

[0088] It can be seen that both the gaseous coolant and the liquid coolant flow along the plate bottom 76 on the bottom face 74 of second core plate 26. Therefore, the flow passages for the liquid and gaseous coolants are co-planar with one another. In order to physically separate the liquid coolant flow from the gaseous coolant flow, the plate bottom 76 of second core plate 26 is provided with an upstanding rib 98 which extends substantially transversely between opposite sides of the plate 26, and divides the plate bottom 76 into a gaseous coolant flow passage 102 and a liquid coolant flow passage 104. The rib 98 has a height which

- 24 -

is the same as the height of the upstanding peripheral wall 78 of second core plate 26, with a flat upper sealing surface 106 which is co-planar with, and joined to, the sealing flange 80.

[0089] As mentioned above, the bottom face 48 of each first core plate 24 in the core 22 is secured and sealed to the top face 72 of an adjacent second core plate 26. Therefore, in the core 22, the top face 46 of each first core plate 24 faces the bottom face 74 of an adjacent second core plate 26. In order to separate the charge air flow passage 51 along the plate bottom 50 of core plate 24 from the coolant flow passages 102, 104 along the plate bottom 76 of core plate 26, a thin, flat separator plate 28 is provided between the top face 46 of each first core plate 24 and the bottom face 74 of each second core plate 26. The separator plate 28 has openings for each of the manifolds, as well as a flat top face 108 which is sealed to the sealing flange 80 and the upper ceiling surface 106 of the second core plate 26, and a flat bottom face 110 which is sealed against the sealing flange 54 of the first core plate 24, for example by brazing. Thus, heat exchange between the charge air and the coolants takes place through the flat separator plate 28.

[0090] The core 22 of heat exchanger 100 is shown as having manifolds which bulge out from the sides of the core 22. It will be appreciated, however, that this configuration is not essential. Rather, the overall shape of the core may be rectangular, with the manifolds located within the rectangular area of the core 22.

[0091] Although not shown in the drawings, some or all of the charge air flow passages 51 and the coolant flow passages 102, 104 in core 22 may be provided with a turbulence-enhancing insert such as a turbulizer or a corrugated fin. Each turbulizer or fin is received between separator plate 28 and the plate bottom 50 or 76 of a core plate 24 or 26, and may be secured on one or both sides by brazing. As used herein, the terms "corrugated fin" and "turbulizer" are intended to refer to

corrugated turbulence-enhancing inserts having a plurality of axially-extending ridges or crests connected by sidewalls, with the ridges being rounded or flat. As defined herein, a "fin" has continuous ridges whereas a "turbulizer" has ridges which are interrupted along their length, so that axial flow through the turbulizer is tortuous. Turbulizers are sometimes referred to as offset or lanced strip fins, and examples of such turbulizers are described in U.S. Patent No. RE.35,890 (So) and U.S. Patent No. 6,273,183 (So et al.). The patents to So and So et al. are incorporated herein by reference in their entireties. Where a fin or turbulizer is provided in the charge air flow passage 51, it will cover substantially the entire rectangular area of plate bottom 50. Similarly, fins or turbulizers may be provided along the plate bottom 76 of second core plate 26 in the gaseous and liquid coolant flow passages 102, 104.

[0092] Rather than fins or turbulizers, it will be appreciated that the plate bottoms 50, 76 of plates 24, 26 may be provided with turbulence-enhancing projections such as ribs and/or dimples (not shown). Additionally, it will be noted that the planar portions of plate bottoms 50, 76 of adjacent plates 24, 26 are in contact with one another in core 22, and will typically be sealed together by brazing. Holes may be cut into the planar portions of each abutting pair of plate bottoms 50, 76, providing that the holes do not cause a leak path. The holes promote reliable brazing of the plate bottoms 50, 76 to one another, and also reduce the conductive resistance of the double plate thickness of planar portions 50, 76. One or both plates 24, 26 may be provided with such holes, again provided that the holes in adjacent plates 24, 26 do not align to create leak paths. The holes can vary in size and number. For the purpose of illustration, Figure 8 shows a single, large cutout 118 (in dashed lines) in the central portion of plate bottom 50 for improving brazing between plate bottom 50 and the plate bottom 76 of an adjacent plate 26. Figure 10 shows a plurality of small holes 119 in plate 24 and holes 121 in plate 26 to aid in reliably brazing the sheets 24, 26 together. As

shown, the holes 119, 121 do not overlap one another so as to avoid the creation of leak paths through the paired plates 24, 26. Also, it will be appreciated that holes 119, 121 may be provided throughout the planar portions of plate bottoms 50, 76, i.e. excluding the area of rib 98, in which neither 24 or 26 is perforated so as to avoid the formation of leak paths.

[0093] A heat exchanger 200 according to a second embodiment of the invention is now described below with reference to Figures 12-19. The heat exchanger 200 includes a core having a structure which is similar to core 22 of heat exchanger 100. Like elements of heat exchanger 200 are identified by like reference numerals and a detailed description of these elements is omitted below.

[0094] The core 22 of heat exchanger 200 is self-enclosed and does not require an external housing. The heat exchanger 200 may further comprise a bottom plate located at the bottom of core 22, a top plate located at the top of core 22, a base plate for mounting, and inlet and outlet fittings for the charge air and the two coolants, none of which are shown in the drawings.

[0095] The core 22 is made up of a plurality of core plates which are joined together face-to-face in order to form alternating flow passages for charge air and the two coolants. Core 22 includes a plurality of first core plates 24 and a plurality of second core plates 26. Although the core 22 of heat exchanger 200 is self-enclosed and is made up of core plates 24, 26 joined together face-to-face, it will be appreciated that the heat exchanger 200 may instead be made up of a stack of dished plates, having nesting upstanding edges. Alternatively, a bar and plate (skeleton) construction may be used for the heat exchanger, although this configuration is less amenable to high volume production.

[0096] The core 22 of heat exchanger 200 includes a charge air inlet manifold 30 which is made up of aligned charge air inlet openings 32 and 34 in respective core plates 24 and 26. The core 22 also comprises a charge air outlet manifold 38 made up of aligned charge air outlet openings 40 and 42 of respective core plates 24 and 26.

[0097] As best seen in the cross-sections of Figures 17 and 19, the plate bottom 50 of first core plate 24 is co-planar with the charge air inlet and outlet openings 32, 40, such that the flow passage 51 for charge air is defined by the space between the top face 46 of first core plate 24 and the bottom face 74 of an adjacent second core plate 26.

[0098] The gaseous coolant inlet manifold 56 and gaseous coolant outlet manifold 64 are in communication with a gaseous coolant flow passage 102 which is located between the bottom face 48 of a first core plate 24 and the top face 72 of a second core plate 26. It can be seen that the gaseous coolant inlet and outlet openings 58 and 66 of first core plate 24 are sealed from the charge air flow passage by the upstanding wall 52 and sealing surface 54 which completely surround openings 58 and 66. However, the gaseous coolant inlet and outlet openings 60 and 68 of the second core plate 26 are in flow communication with the plate bottom 76 such that each gaseous coolant flow passage 102 is defined between the top face 72 of a second core plate and the bottom face 48 of an adjacent first core plate 24.

[0099] Similarly, the liquid coolant inlet and outlet manifolds 82 and 90 are defined by respective liquid coolant inlet openings 84, 86 and liquid coolant outlet openings 92, 94. The liquid coolant inlet and outlet openings 86, 94 of second core plate 26 are in flow communication with the plate bottom 76, and therefore each

liquid coolant flow passage 104 is defined between the plate bottom 76 of a second core plate 26 and the plate bottom 50 of an adjacent first core plate 24.

[00100] It can be seen that the configuration of plates 24, 26 in heat exchanger 200 eliminates the need for the flat separator plate 28 of heat exchanger 100. However, as shown in Figure 19, the charge air flow passages 51 of heat exchanger 200 have bypass channels 120 at their edges, caused by the presence of an upwardly-extending sealing rib (in the form of upstanding wall 52) extending upwardly from the top face 46 of plate 24, and an adjacent sealing rib 122 extending downwardly from the bottom face 48 of plate 24. The sealing rib 122 seals to a corresponding rib 124 projecting upwardly from the plate bottom of an adjacent core plate 26 to seal the edges of a coolant flow passage 102, 104. The bypass channel 120 extends continuously between the charge air inlet and outlet manifolds 30, 38 and creates low pressure drop passages for the charge air in each of the charge air flow passages. These bypass channels 120 can be partially or completely eliminated by local deformation of the plate in this region to create a rib which partly or completely blocks the bypass channel 120. For example, as shown in Figure 19, the edge of plate bottom 50, which is raised relative to sealing rib 122 and bypass channel 120, is deformed outwardly toward upstanding wall 52 so as to form a blocking rib 126 which partially blocks the bypass channel 120 while leaving sufficient contact area between sealing ribs 122, 124 to maintain an effective seal. It will be appreciated that several blocking ribs 126 can be provided along the bypass channel 120, along both long sides of plate 24.

[00101] Although the invention has been described with reference to certain embodiments, it is not limited thereto. Rather, the invention includes all embodiments which may fall within the following claims.

What is claimed is:

1. A method for cooling a pressurized cathode air stream in a fuel cell system comprising a fuel cell stack, a first charge air cooler comprising a gas-to-gas charge air cooler, a gas-to-gas humidifier, and a second charge air cooler, wherein the method comprises:

(a) providing said pressurized cathode air stream having a first temperature (T_1);

(b) passing said pressurized cathode air stream through said first charge air cooler in heat exchange with a cathode exhaust gas stream from said fuel cell stack, wherein said cathode exhaust gas stream has a second temperature (T_2) at an inlet of said first charge air cooler and said pressurized cathode air stream is cooled to a third temperature (T_3) at an outlet of said first charge air cooler;

(c) passing said pressurized cathode air stream through said second charge air cooler in heat exchange with a liquid or gaseous coolant having a fourth temperature (T_4) at a coolant inlet of said liquid-to-gas charge air cooler, wherein said pressurized cathode air stream is cooled to a fifth temperature (T_5) at an outlet of said second charge air cooler;

(d) passing said pressurized cathode air stream and said cathode exhaust stream through said gas-to-gas humidifier, wherein water vapour is transferred from the cathode exhaust stream to the pressurized cathode air stream in said humidifier; and

(e) passing said pressurized cathode air stream to a cathode air inlet of said fuel cell stack;

wherein said cathode exhaust stream passes through said gas-to-gas humidifier before passing through said first charge air cooler; and wherein said pressurized cathode air stream passes through said humidifier after it passes

- 30 -

through said second charge air cooler and before it enters the cathode air inlet of said fuel cell stack.

2. The method of claim 1, wherein $T_2 < T_3 < T_1$ under normal operating conditions.
3. The method of claim 1 or 2, wherein $T_4 < T_5 < T_3$ under normal operating conditions.
4. The method of any one of claims 1 to 3, wherein the cathode exhaust gas stream is at a sixth temperature (T_6) at an inlet of said gas-to-gas humidifier and wherein the pressurized cathode air stream is at a seventh temperature (T_7) at an outlet of the gas-to-gas humidifier, wherein $T_5 < T_7 < T_6$ under normal operating conditions.
5. The method of claim 4, wherein $T_2 < T_6$ under normal operating conditions.
6. The method of any one of claims 1 to 5, wherein the second charge air cooler is a liquid-to-gas charge air cooler and wherein the liquid coolant absorbs heat from one or more other heat sources within the fuel cell system.
7. The method of any one of claims 1 to 6, wherein the amount of thermal energy removed from the pressurized cathode air stream by the first charge air cooler is greater than the amount of thermal energy removed from the pressurized cathode air stream by the second charge air cooler.
8. A system for producing a pressurized cathode air stream for use in a fuel cell, comprising:

- 31 -

(a) a first charge air cooler comprising a gas-to-gas charge air cooler for cooling said pressurized cathode air stream from a first temperature (T_1) to a third temperature (T_3) with a gaseous coolant having a second temperature (T_2) at an inlet of the first charge air cooler;

(b) a second charge air cooler for cooling said pressurized cathode air stream from T_3 to a fifth temperature (T_5) with a liquid or gaseous coolant having a fourth temperature (T_4) at a coolant inlet of said second charge air cooler;

(c) a gas-to-gas humidifier for increasing a water content of the pressurized cathode air stream by transfer of water from a humidifying gas; and

(d) a fuel cell stack having a cathode air inlet and a cathode exhaust gas outlet;

wherein the humidifying gas comprises a cathode exhaust gas stream from the cathode exhaust gas outlet of the fuel cell stack;

the gaseous coolant of the first charge air cooler comprises the cathode exhaust gas stream;

the first charge air cooler is arranged to receive the cathode exhaust gas stream from the humidifier and the humidifier is arranged to receive the cathode exhaust gas stream from the cathode exhaust gas outlet of the fuel cell stack.

9. The system of claim 8, wherein the first charge air cooler and the second charge air cooler are arranged sequentially such that the second charge air cooler receives said pressurized cathode air stream at said third temperature (T_3) from said first charge air cooler.

10. The system of claim 8 or 9, wherein the second charge air cooler is a liquid-to-gas charge air cooler, and wherein the first charge air cooler and the second charge air cooler are integrated into a three-fluid charge air cooler comprising a plurality of flow passages for said pressurized cathode air stream, a plurality of flow

passages for said gaseous coolant, and a plurality of flow passages for said liquid coolant.

11. The system of any one of claims 8 to 10, wherein the cathode air inlet receives said pressurized cathode air stream from said gas-to-gas humidifier.

12. The system of any one of claims 8 to 11, further comprising a compressor which receives air at ambient temperature and pressure and compresses said ambient air to produce said pressurized cathode air stream at said first temperature (T_1), and wherein the first charge air cooler receives the pressurized cathode air stream from the compressor.

13. The system of any one of claims 8 to 12, wherein the gas-to-gas humidifier is a membrane humidifier.

14. The system of claim 8 or 9, wherein the second charge air cooler is a gas-to-gas charge air cooler, wherein the second charge air cooler is cooled by a variable speed fan, and wherein the variable speed fan is controlled by a control circuit so as to maintain the temperature T_7 within a desired range.

15. The system of any one of claims 8 to 13, wherein the second charge air cooler is a liquid-to-gas charge air cooler in which the pressurized cathode air stream is cooled by a liquid coolant which circulates through a cooling circuit which also includes the fuel cell stack, and wherein the cooling circuit includes a variable speed pump which controls the flow of the liquid coolant through the fuel cell stack and the second charge air cooler.

16. A three-fluid charge air cooler comprising a plurality of plates arranged in a plate stack having a first end and a second end and a length extending from the first end to the second end, the plate stack being divided along its length into a first portion and a second portion, the charge air cooler having a plurality of charge air flow passages alternating throughout the stack with a plurality of first coolant flow passages and with a plurality of second coolant flow passages, wherein the three-fluid charge air cooler further comprises:

- a charge air inlet manifold and a charge air outlet manifold in flow communication with the plurality of charge air flow passages, wherein the charge air inlet manifold and the charge air outlet manifold are located proximate to opposite ends of the plate stack;

- a first coolant inlet manifold and a first coolant outlet manifold in flow communication with the plurality of said first coolant flow passages, wherein the first coolant flow passages extend along the second portion of the plate stack, wherein, the first coolant inlet manifold is located at the second end of the plate stack, and the first coolant outlet manifold is located in the second portion of the plate stack, proximate to said ribs;

- a second coolant inlet manifold and a second coolant outlet manifold in flow communication with the plurality of said second coolant flow passages, wherein the second coolant flow passages extend along the first portion of the plate stack, and wherein the second coolant inlet manifold is located in the first portion of the plate stack, proximate to said ribs, and the second coolant outlet manifold is located at the first end of the plate stack.

17. The three-fluid charge air cooler of claim 16, wherein the inlet and outlet manifolds for the charge air, the first coolant and the second coolant are integrally formed with and enclosed by the plate stack.

- 34 -

18. The three-fluid charge air cooler of claim 17, wherein the charge air flow passages extend along the entire length of the plate stack.

19. The three-fluid charge air cooler of claim 18, further comprising a plurality of ribs dividing the first portion of the stack from the second portion, wherein each of the ribs is formed in one of the plates of the plate stack and extends transversely across said plate to separate one of the first coolant flow passages from one of the second coolant flow passages,

such that the plurality of ribs separate the plurality of first coolant flow passages from the plurality of second coolant flow passages.

20. The three-fluid charge air cooler of any one of claims 16 to 19, wherein the charge air inlet manifold is located at the first end of the plate stack and the charge air outlet manifold is located at the second end of the plate stack.

21. The three-fluid charge air cooler of any one of claims 16 to 20, wherein the plate stack includes a plurality of first core plates and a plurality of second core plates, each of the first core plates and each of the second core plates having a flat plate bottom surrounded by an upstanding wall;

wherein the flat plate bottom of each said first core plate is sealed to the flat plate bottom of an adjacent one of said second core plates, wherein pairs of first and second core plates sealed together along their plate bottoms are separated by flat separator plates.

22. The three-fluid charge air cooler of claim 21, wherein the flat plate bottom of at least one of the first and second core plates in each said pair of plates is provided with at least one hole.

Fig. 1A -Prior Art

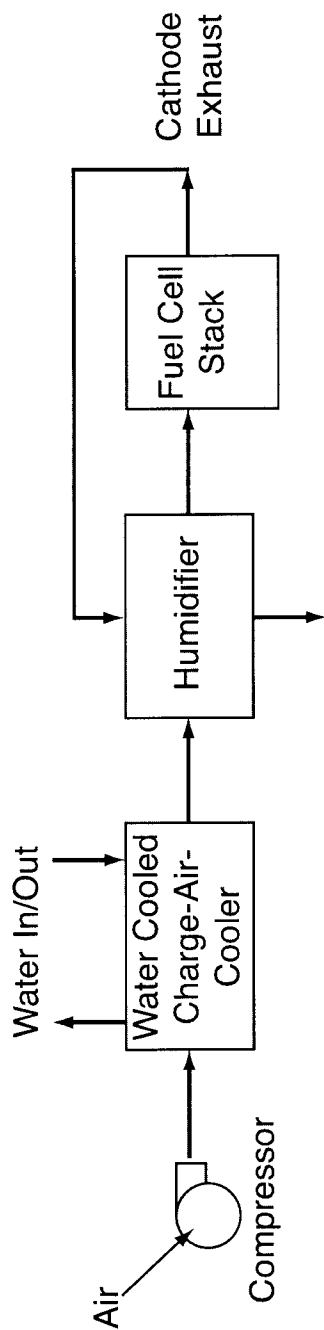
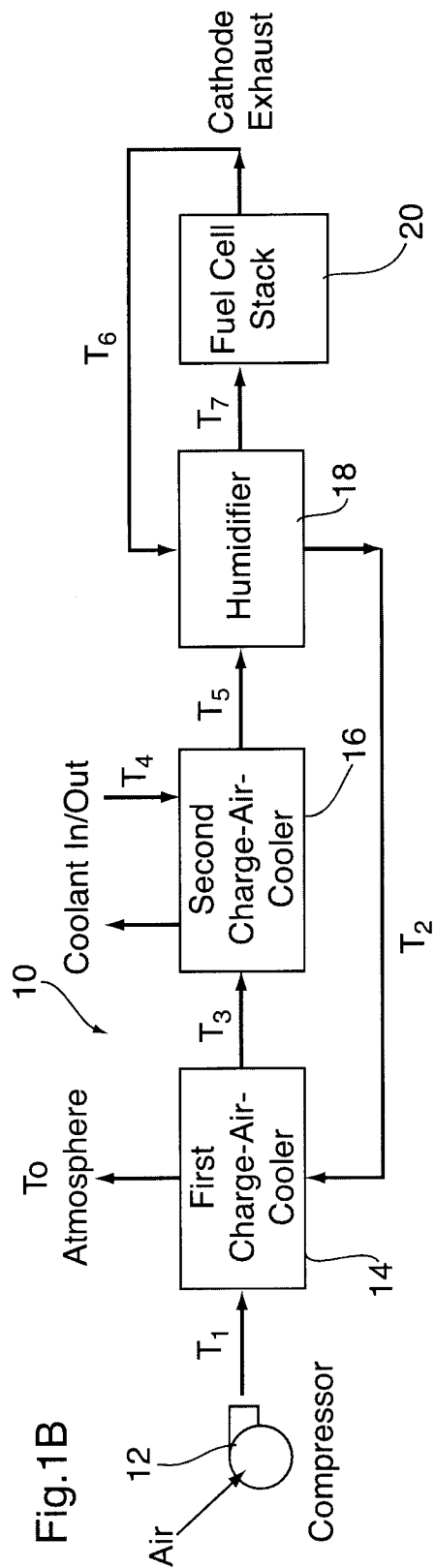
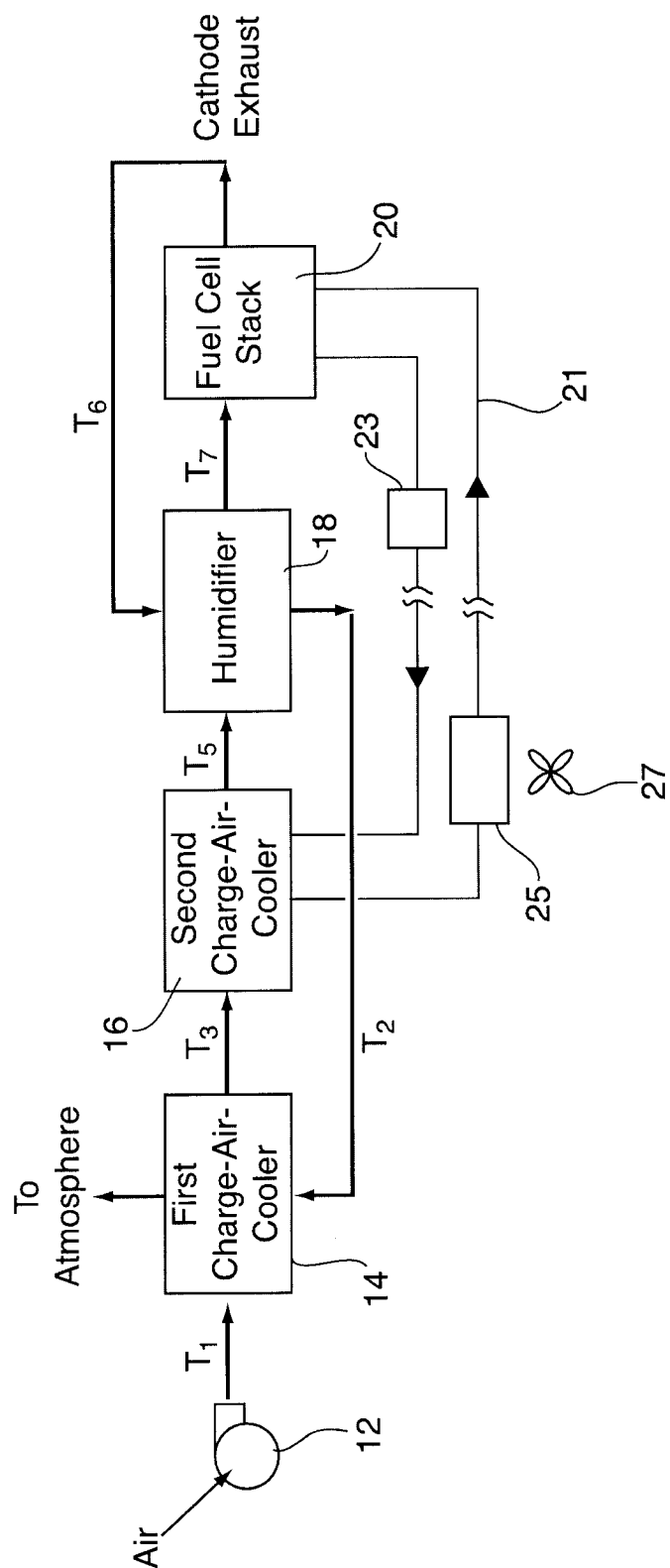


Fig. 1B



2 / 20

Fig.1C



3 / 20

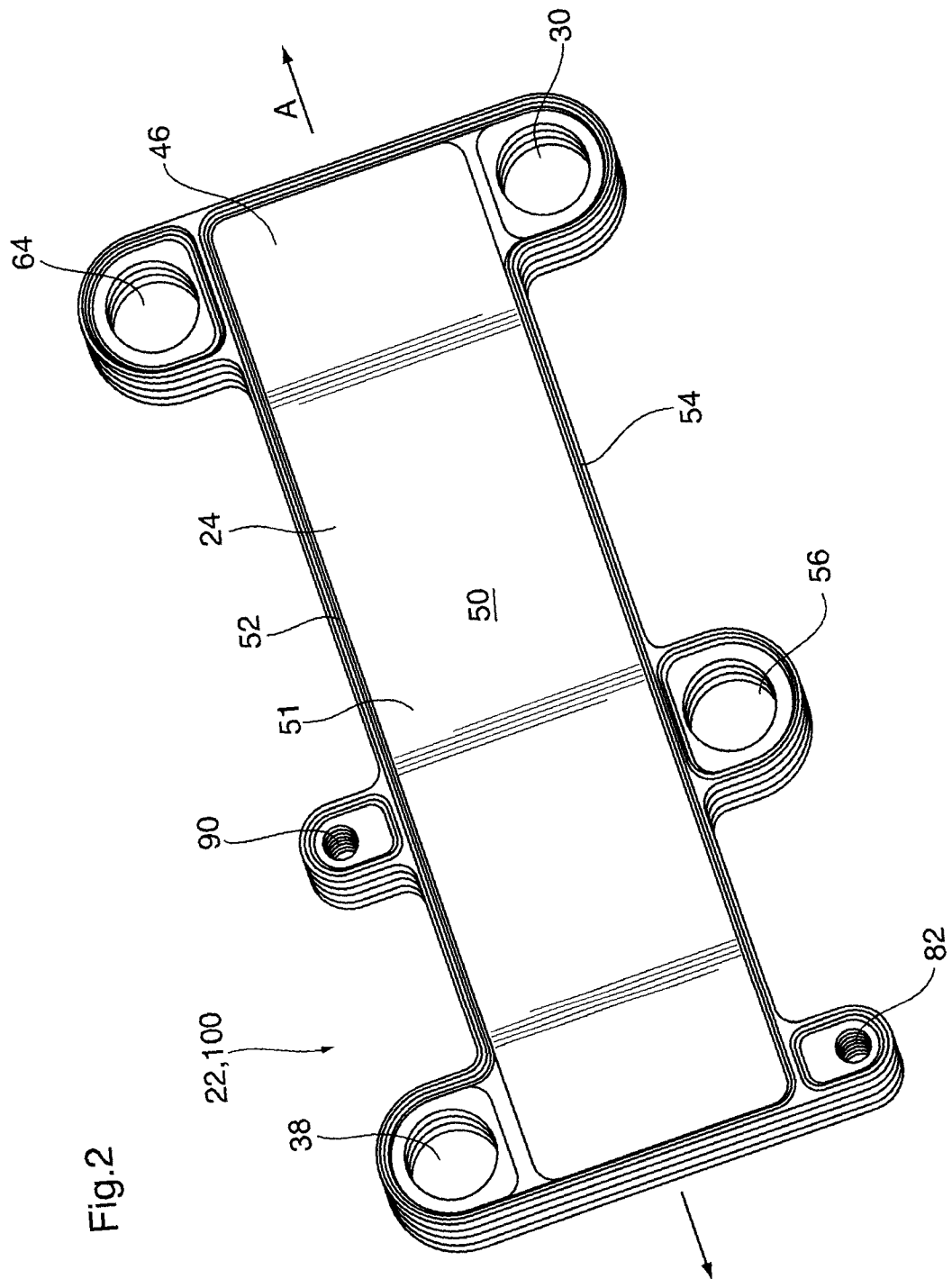


Fig. 2

Fig.3

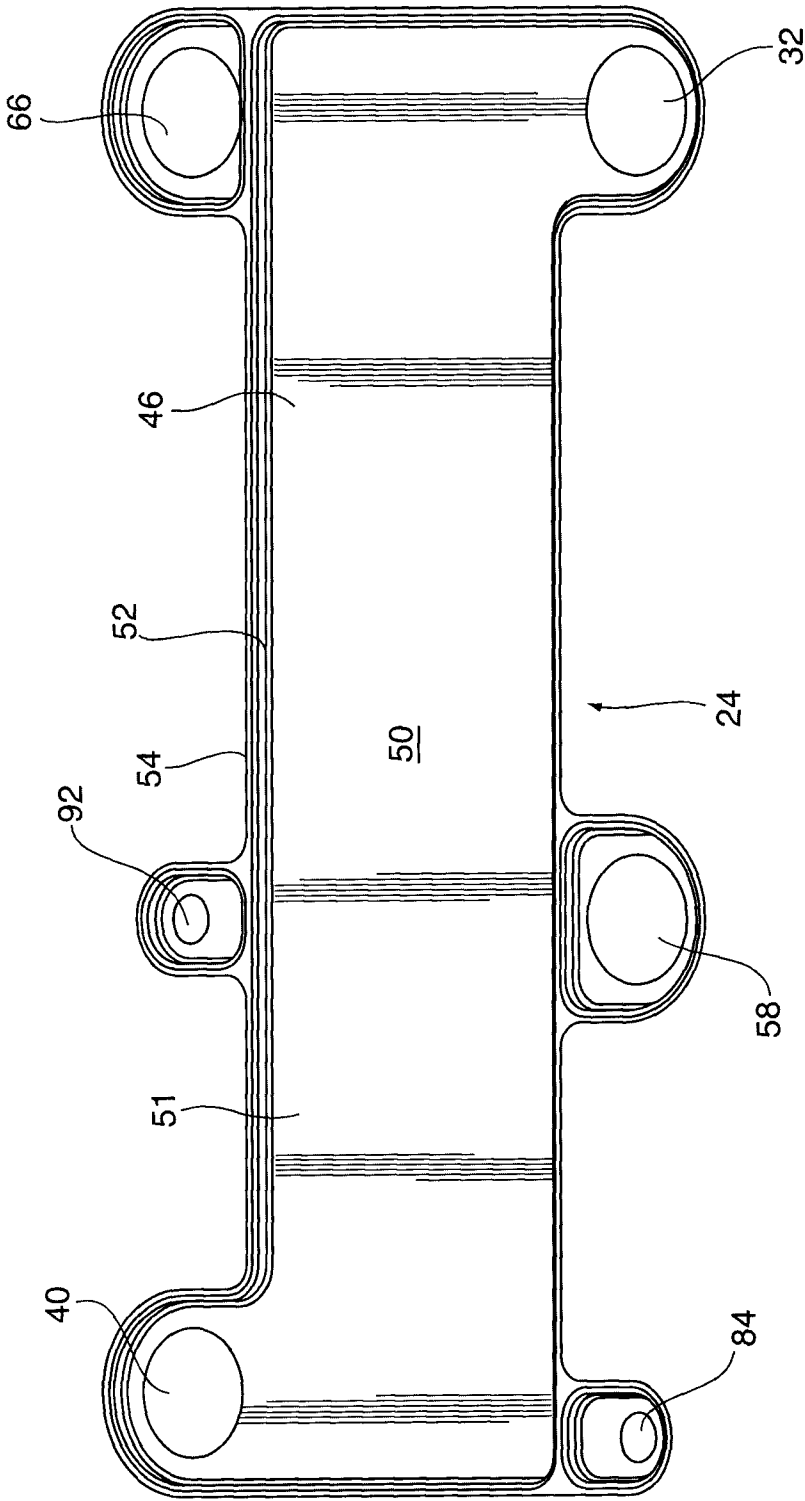


Fig.4

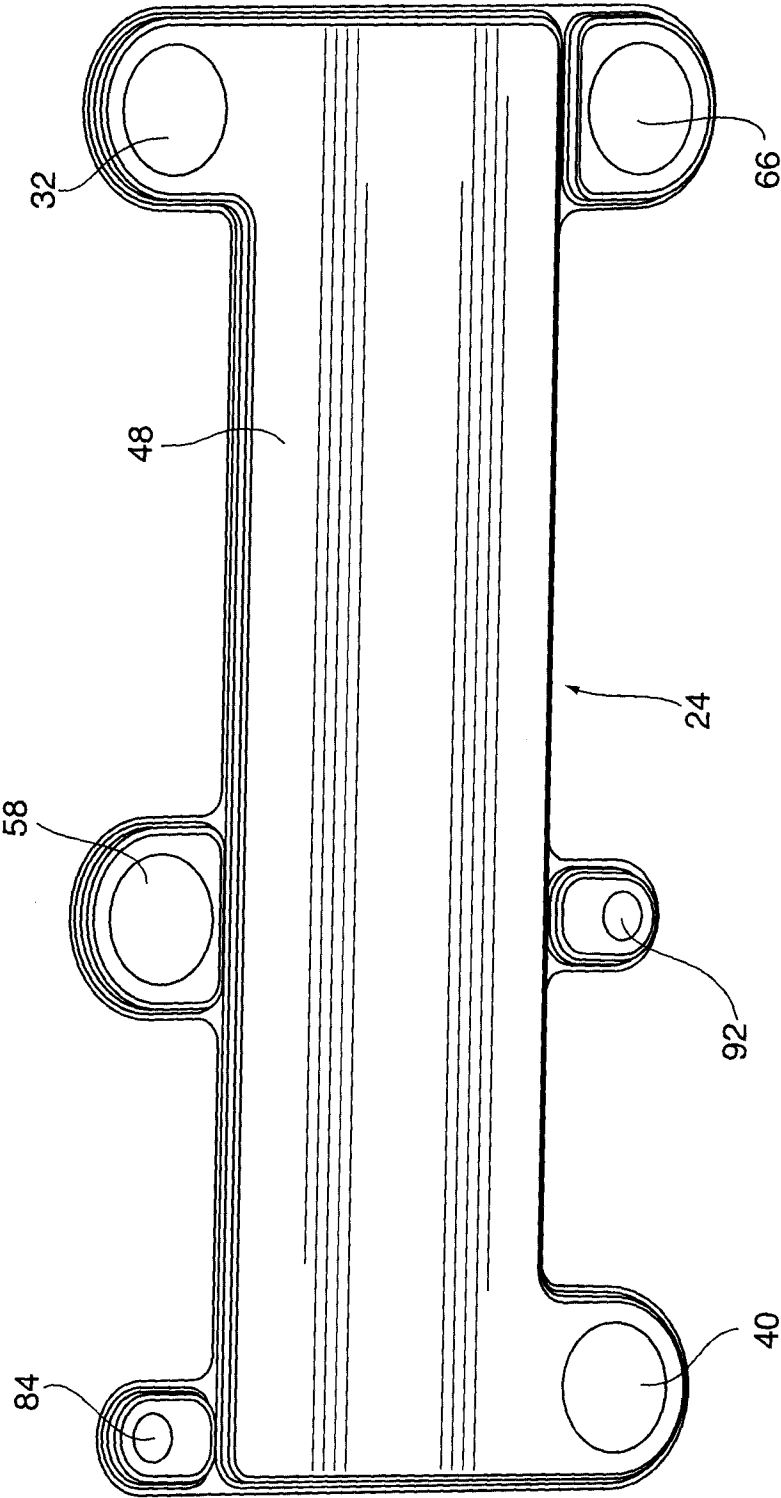
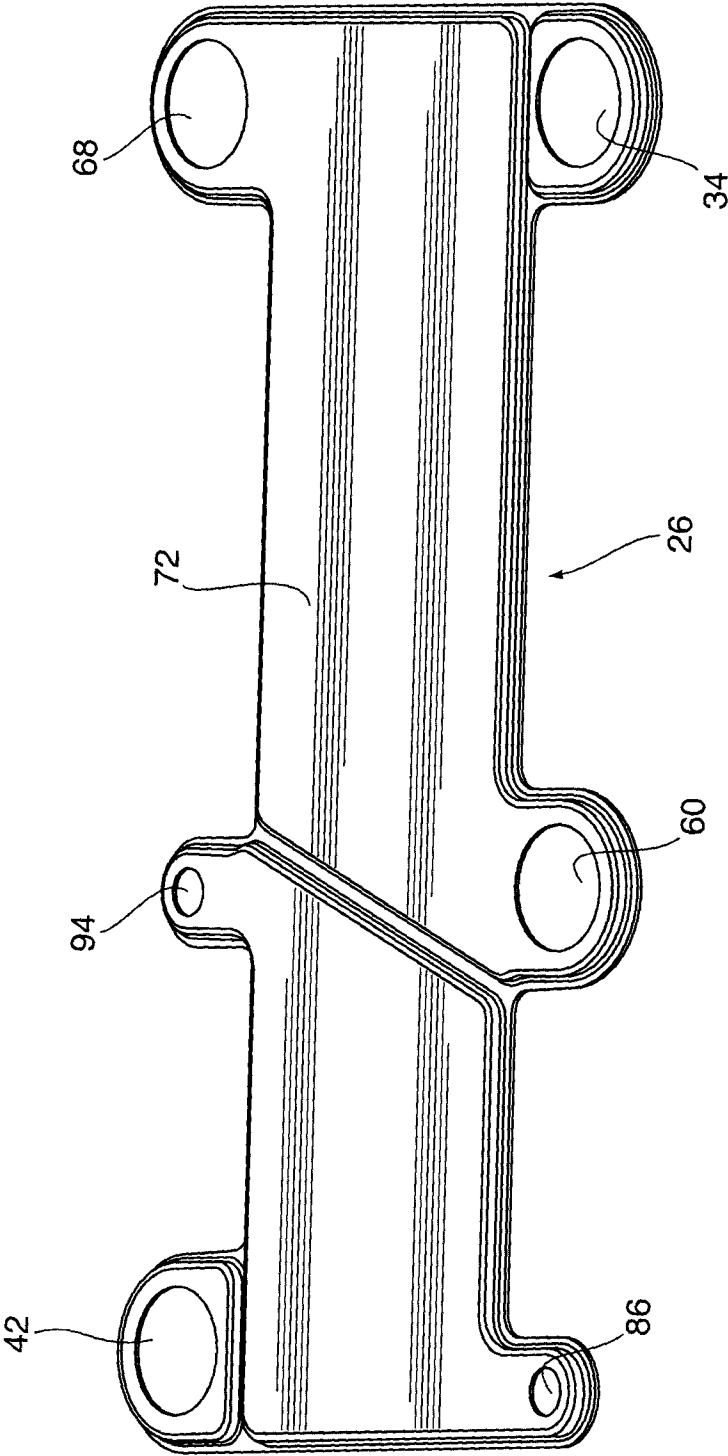


Fig.5



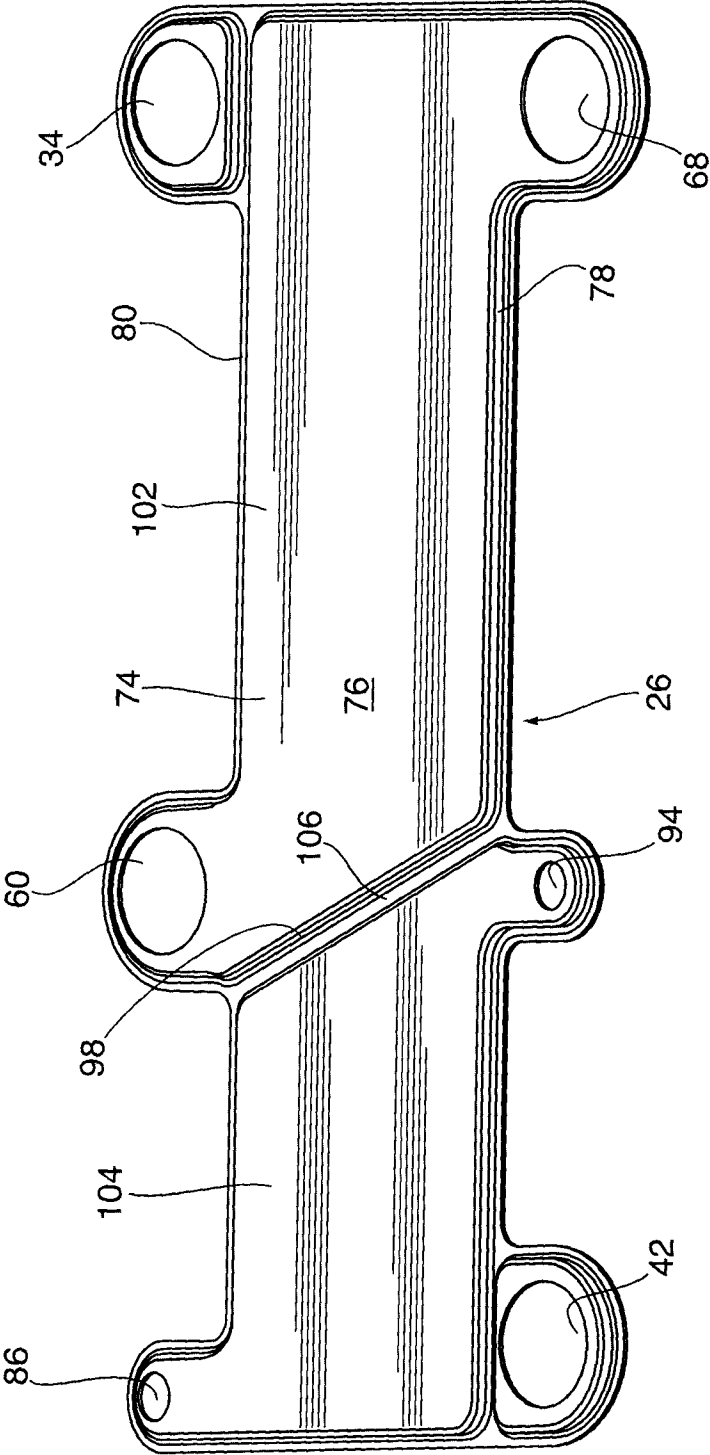


Fig.6

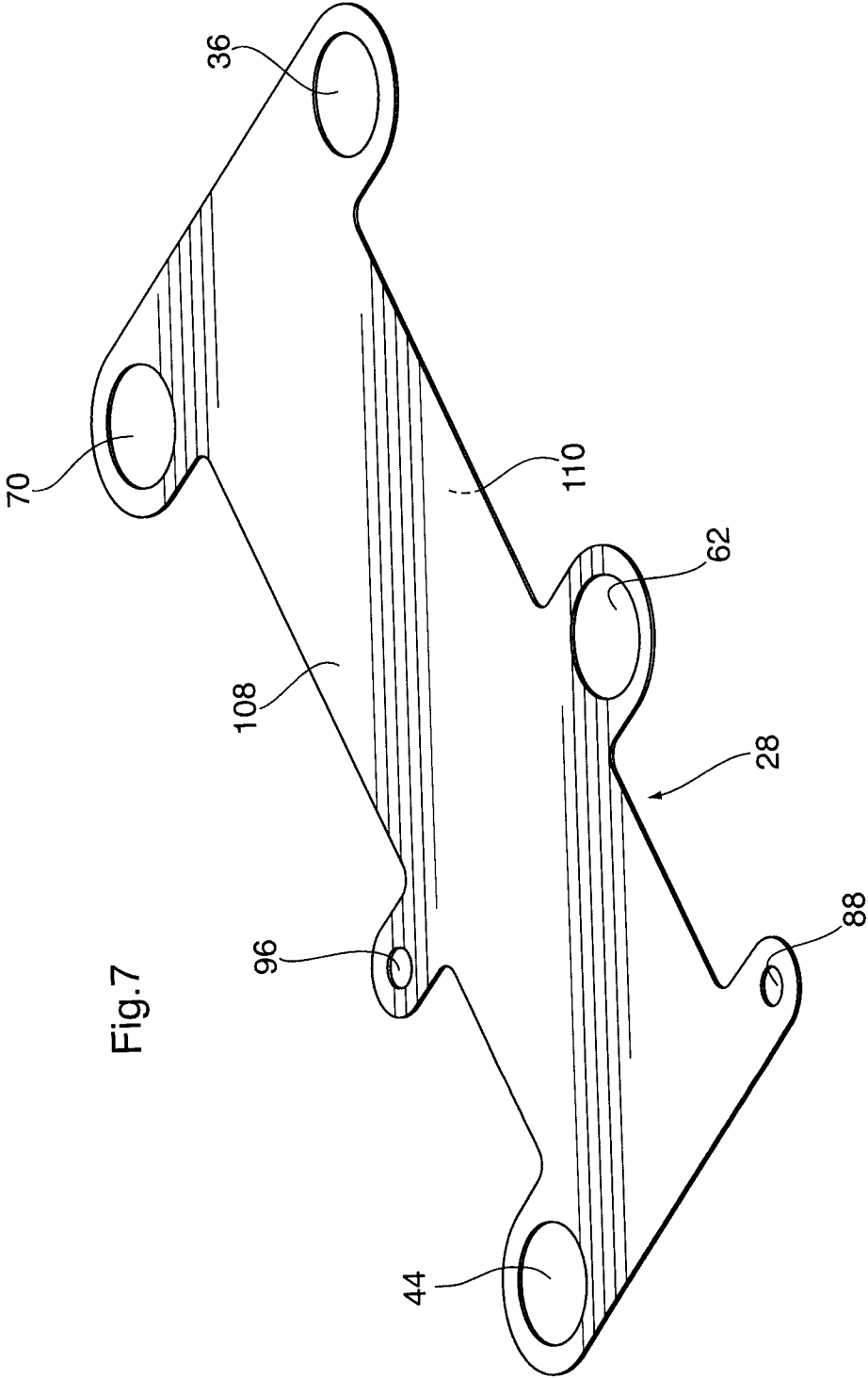


Fig. 7

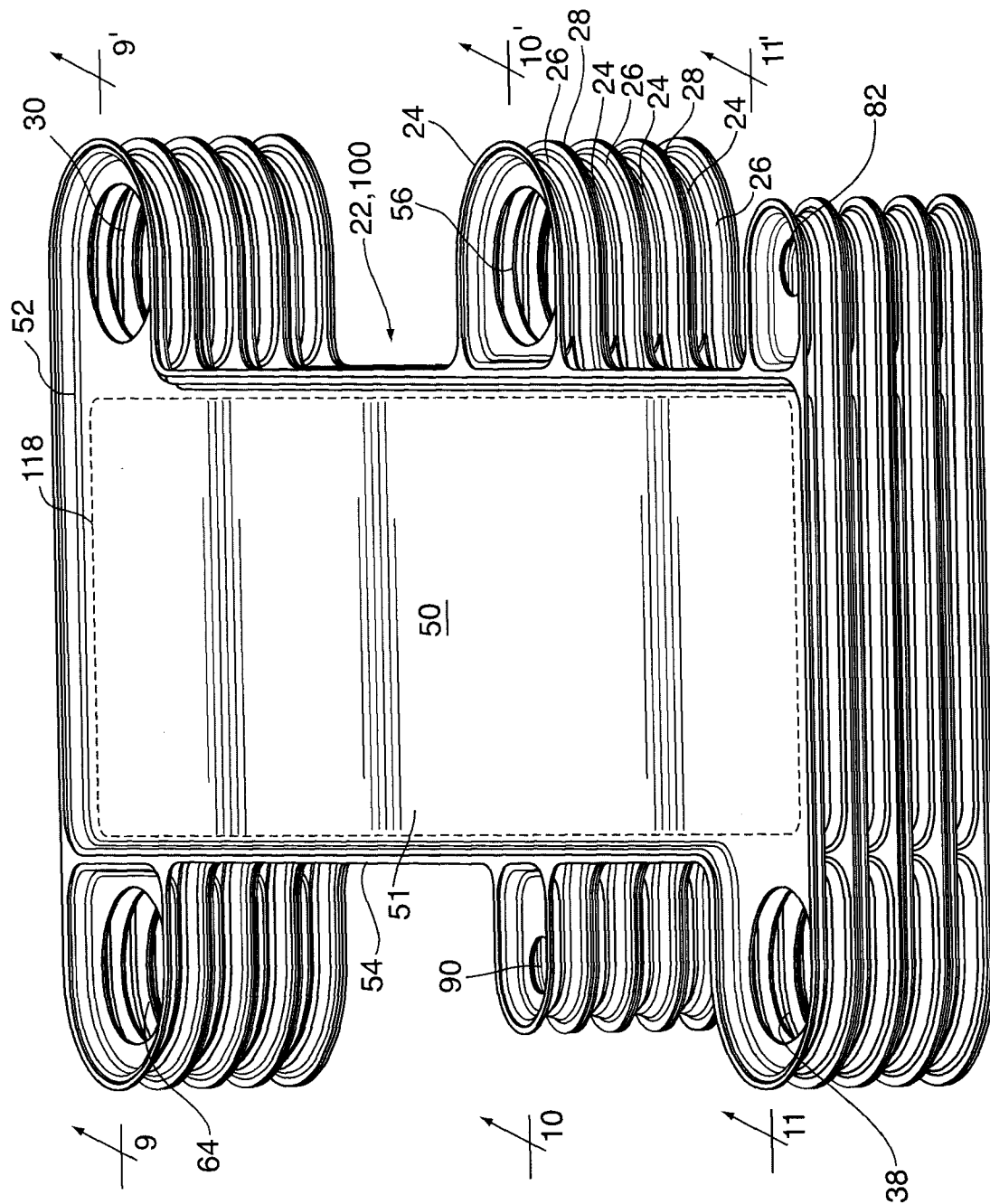
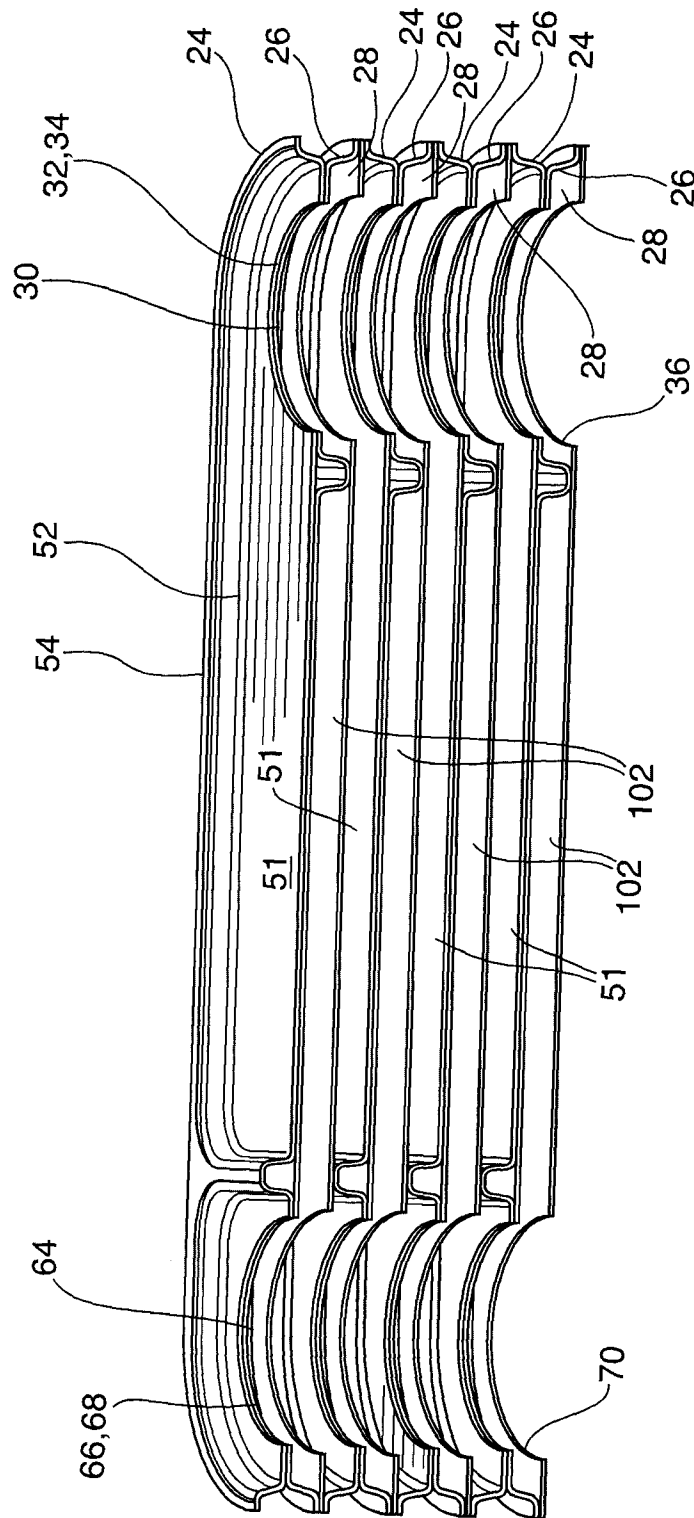
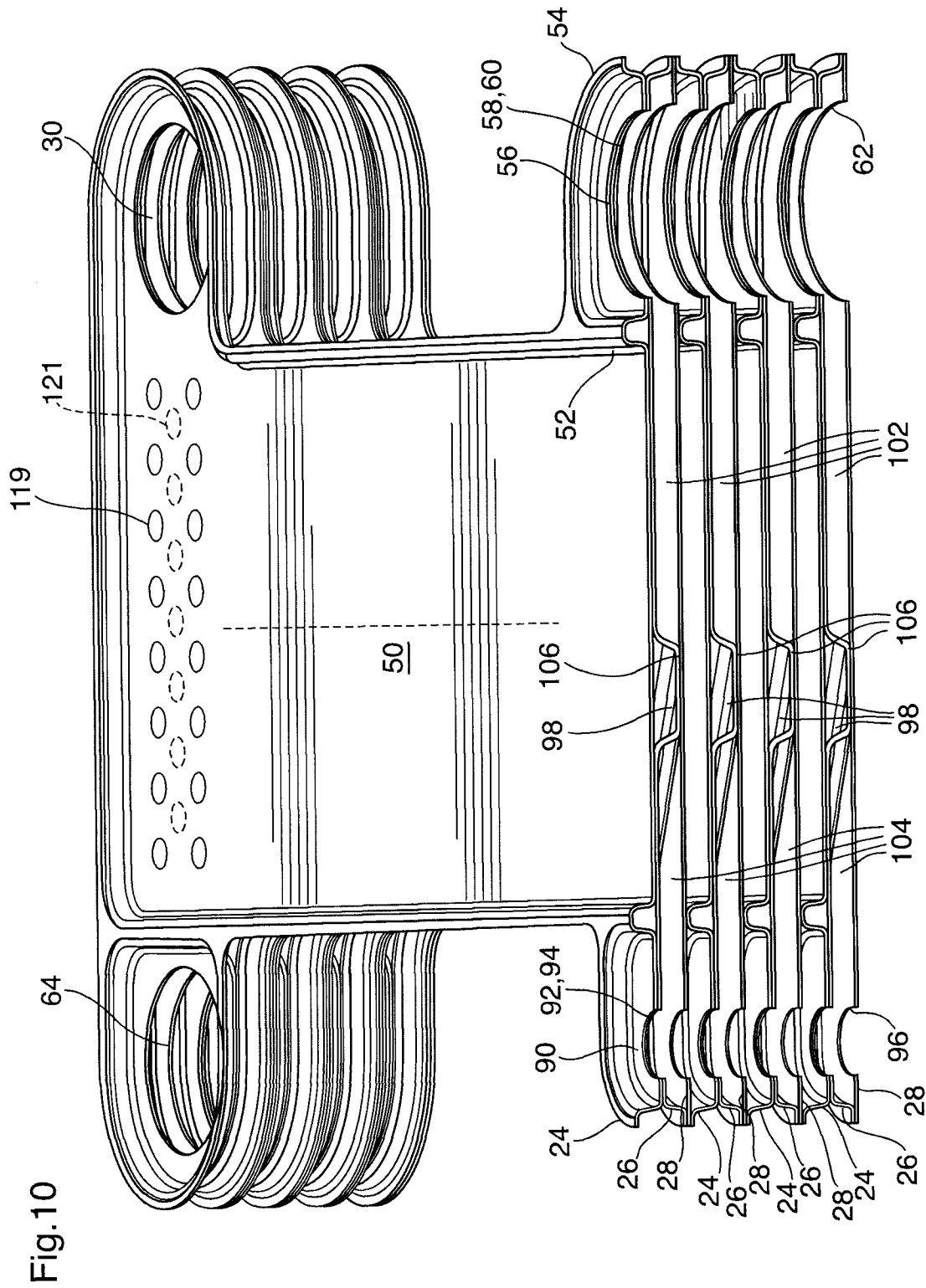
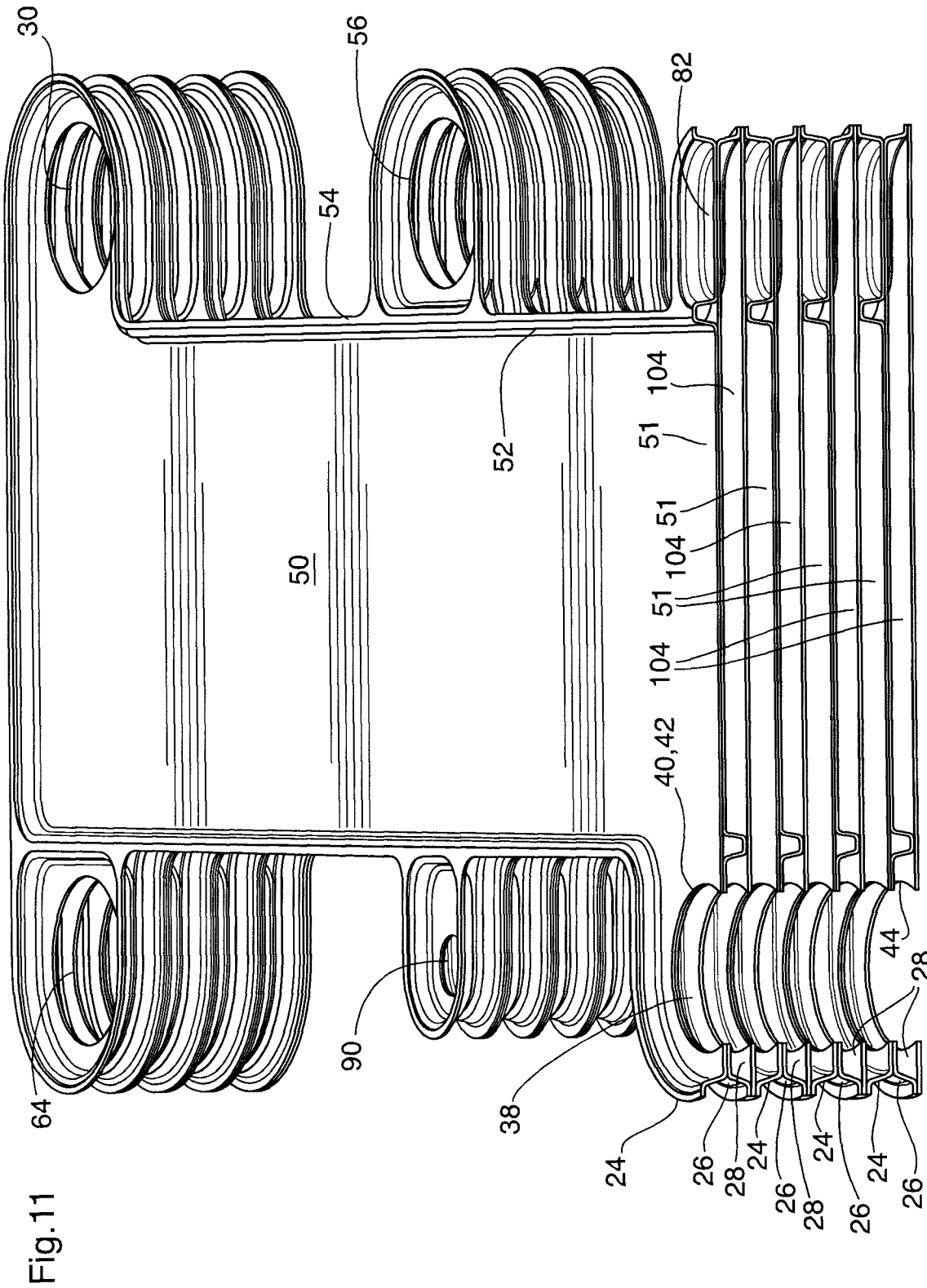


Fig. 8

Fig.9







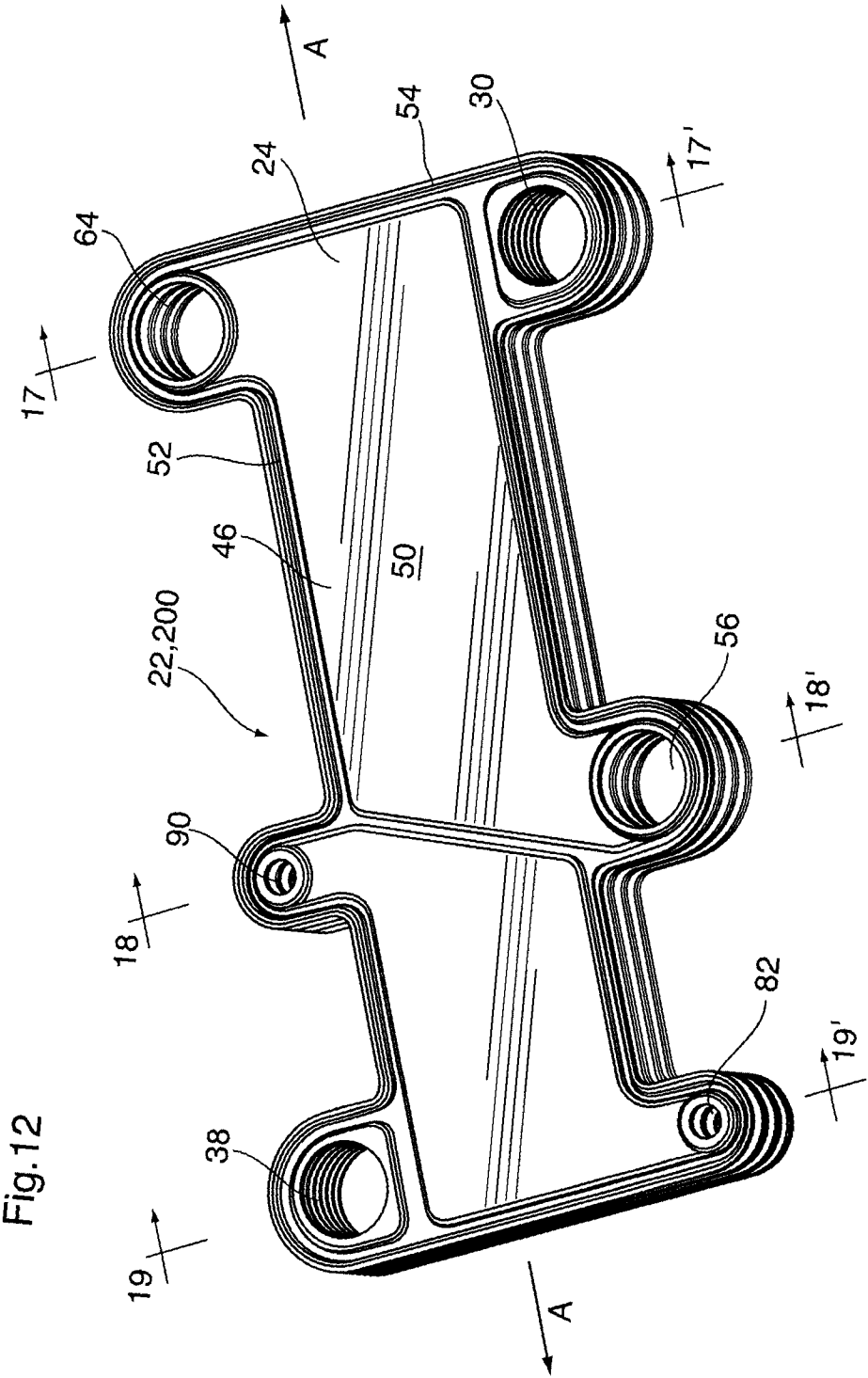


Fig.13

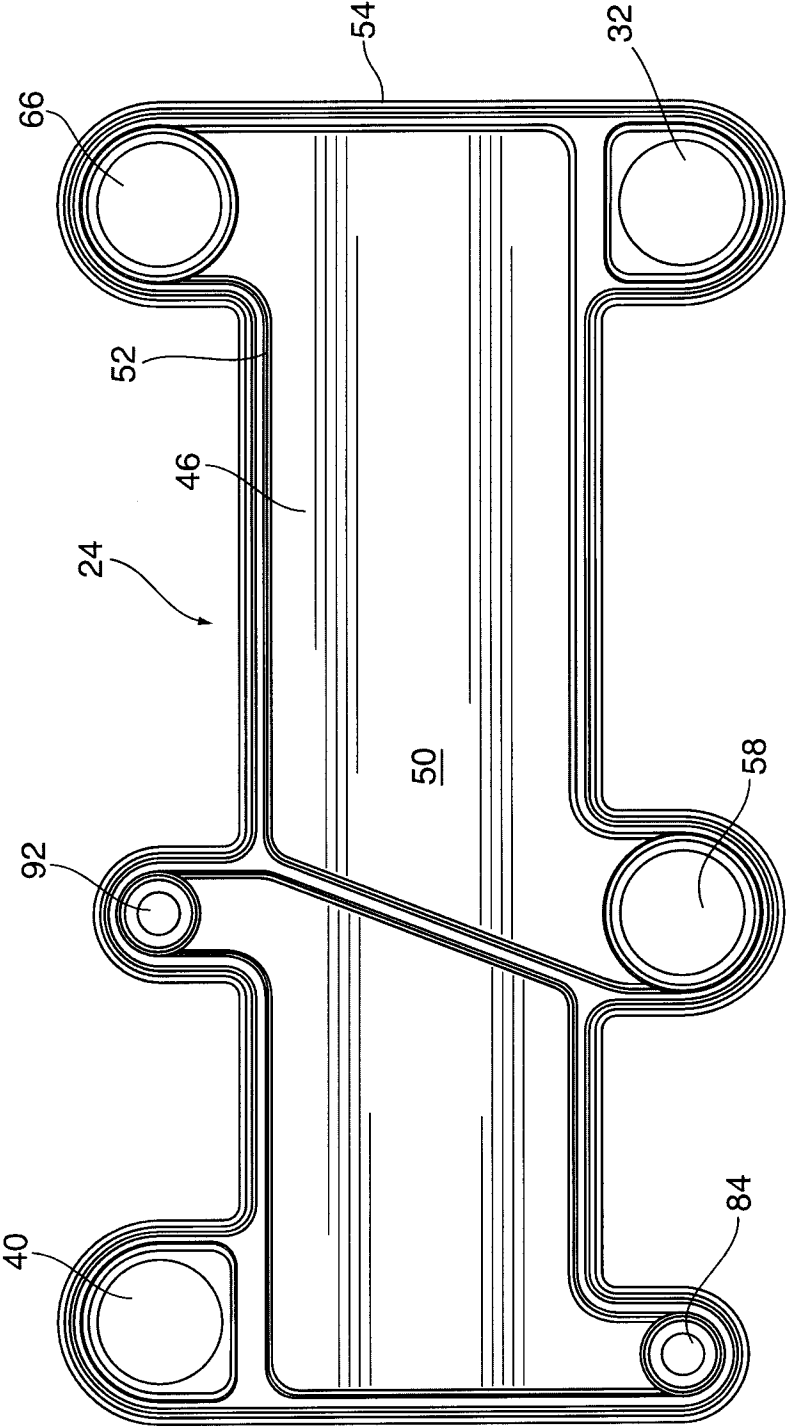


Fig.14

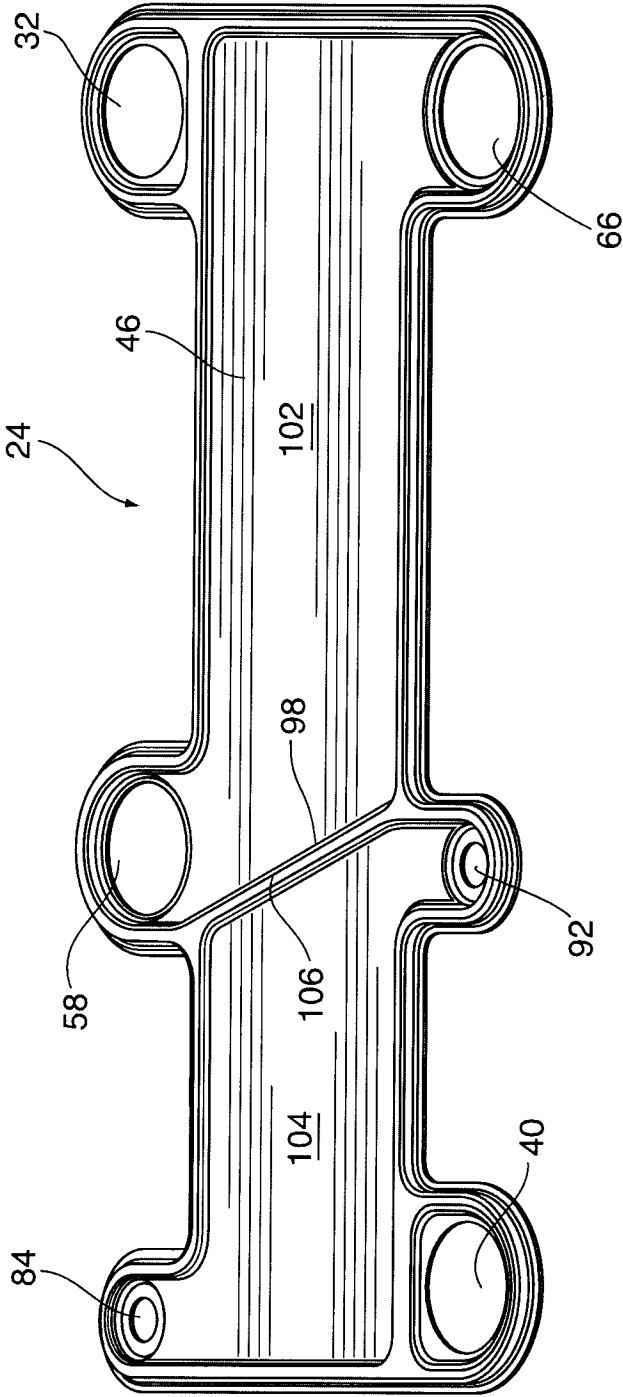
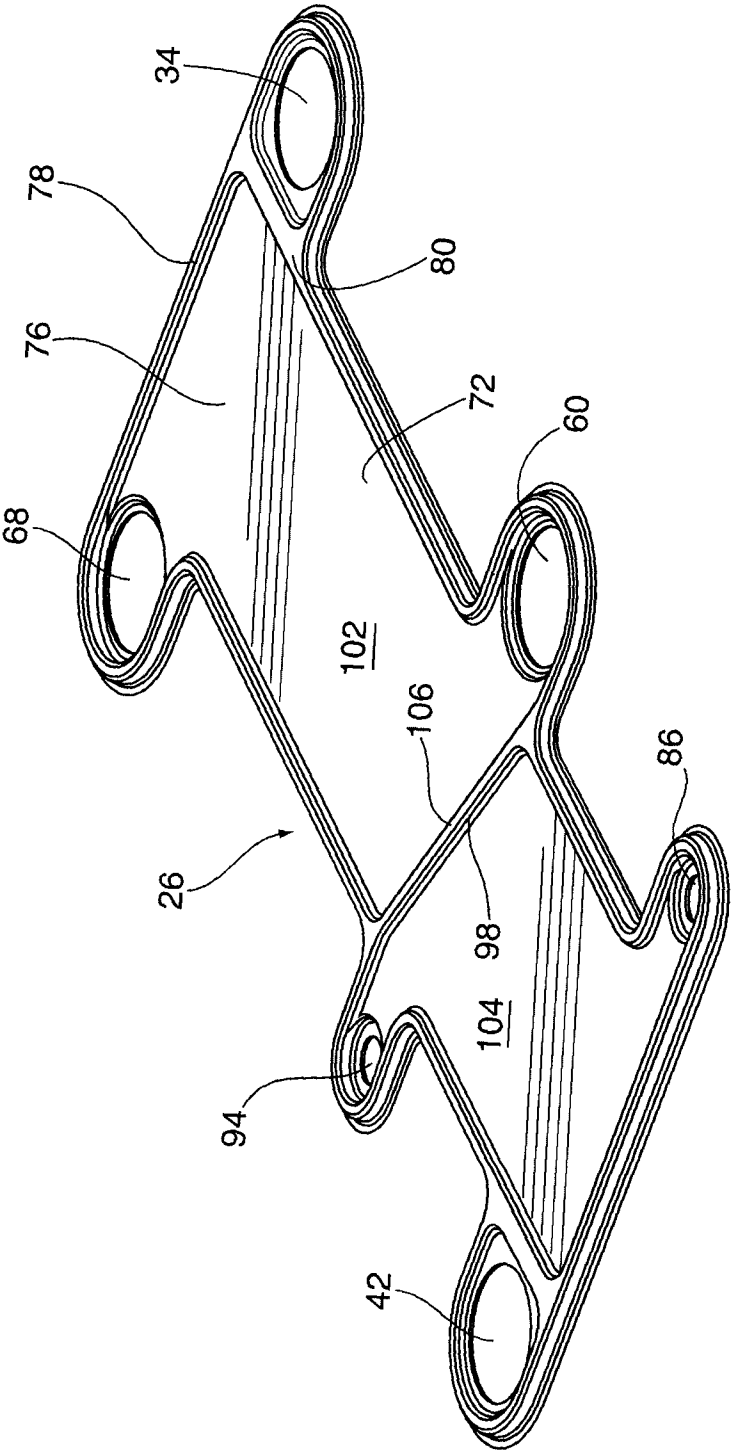


Fig.15



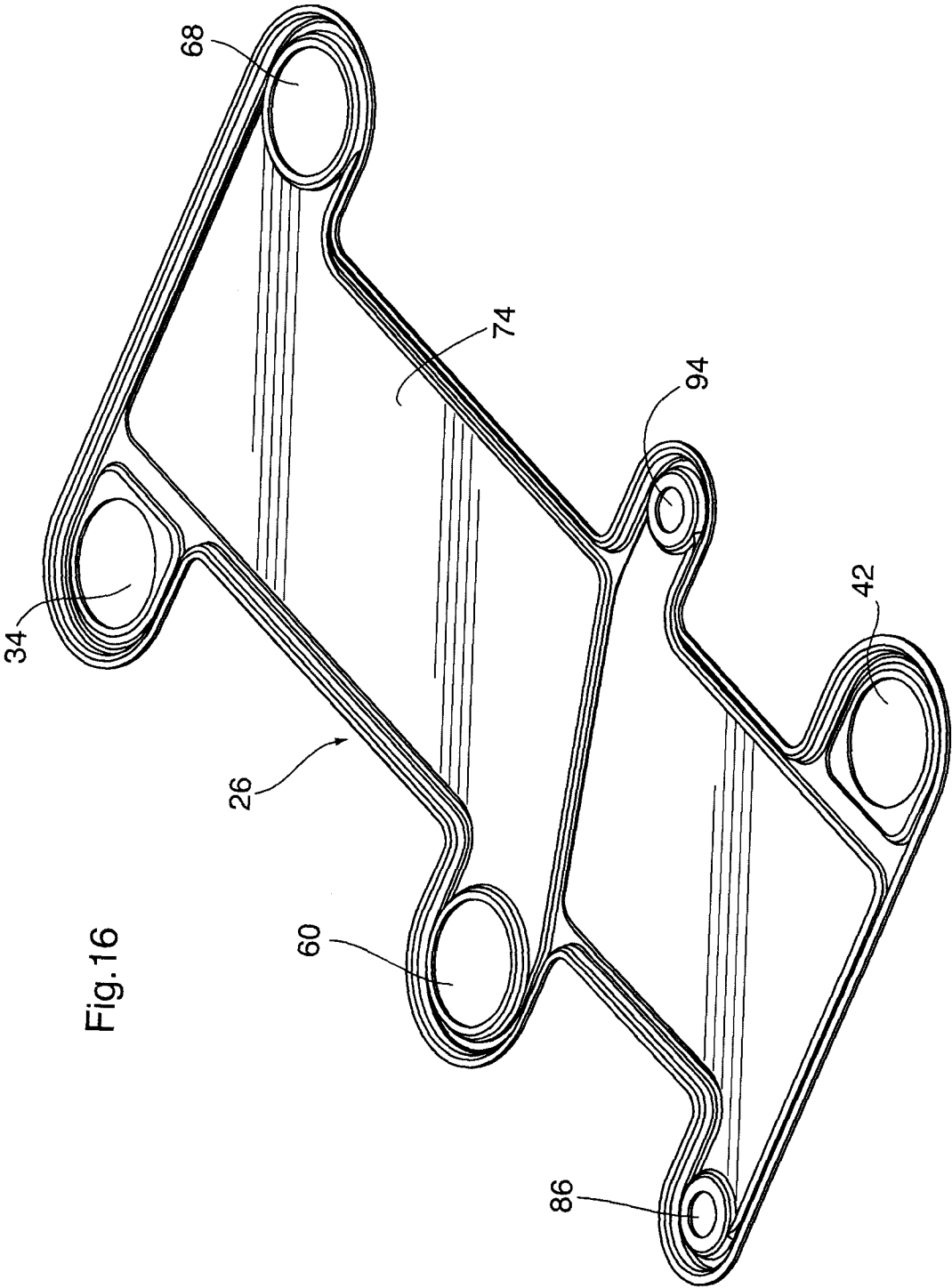
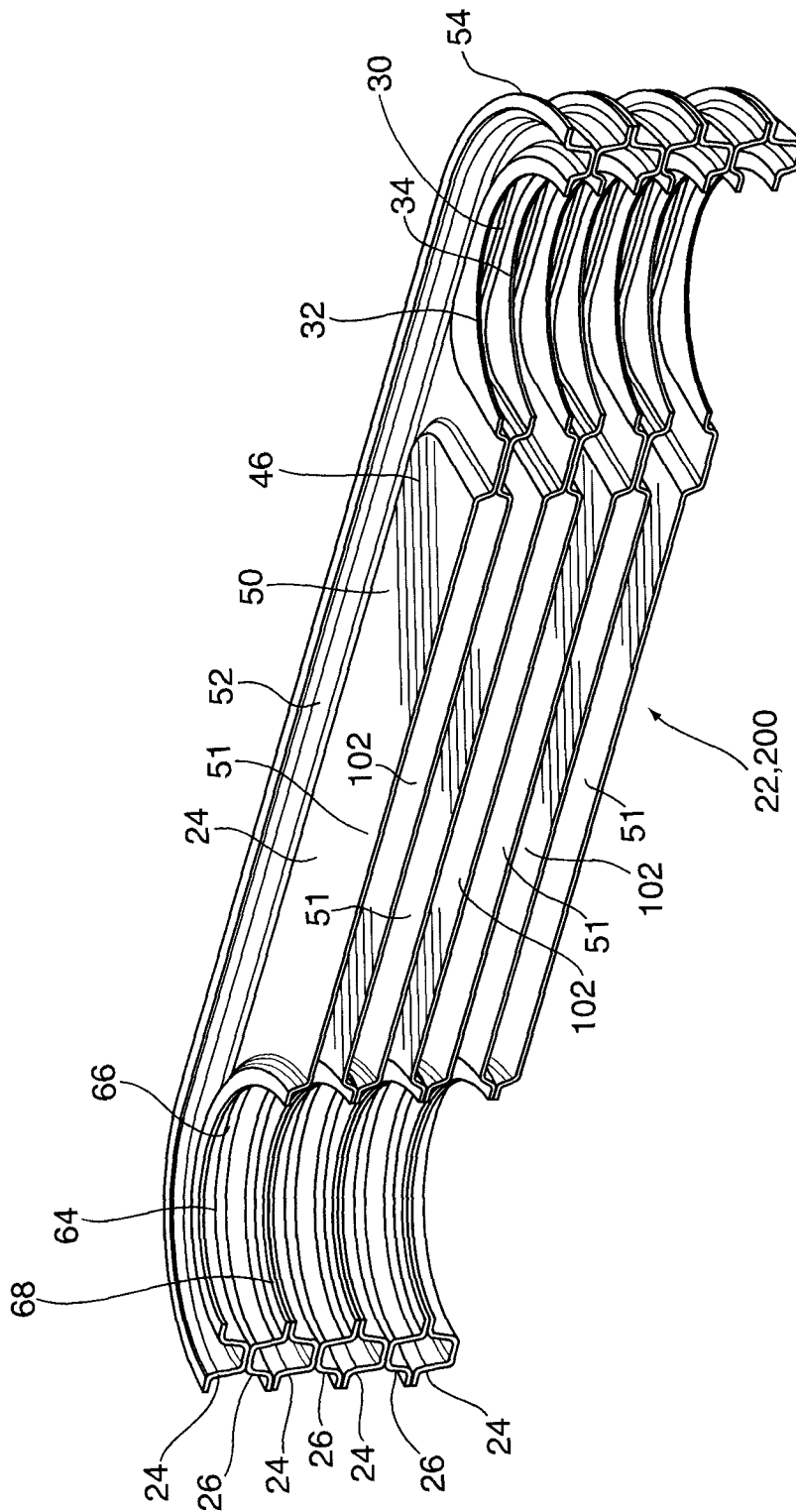


Fig. 16

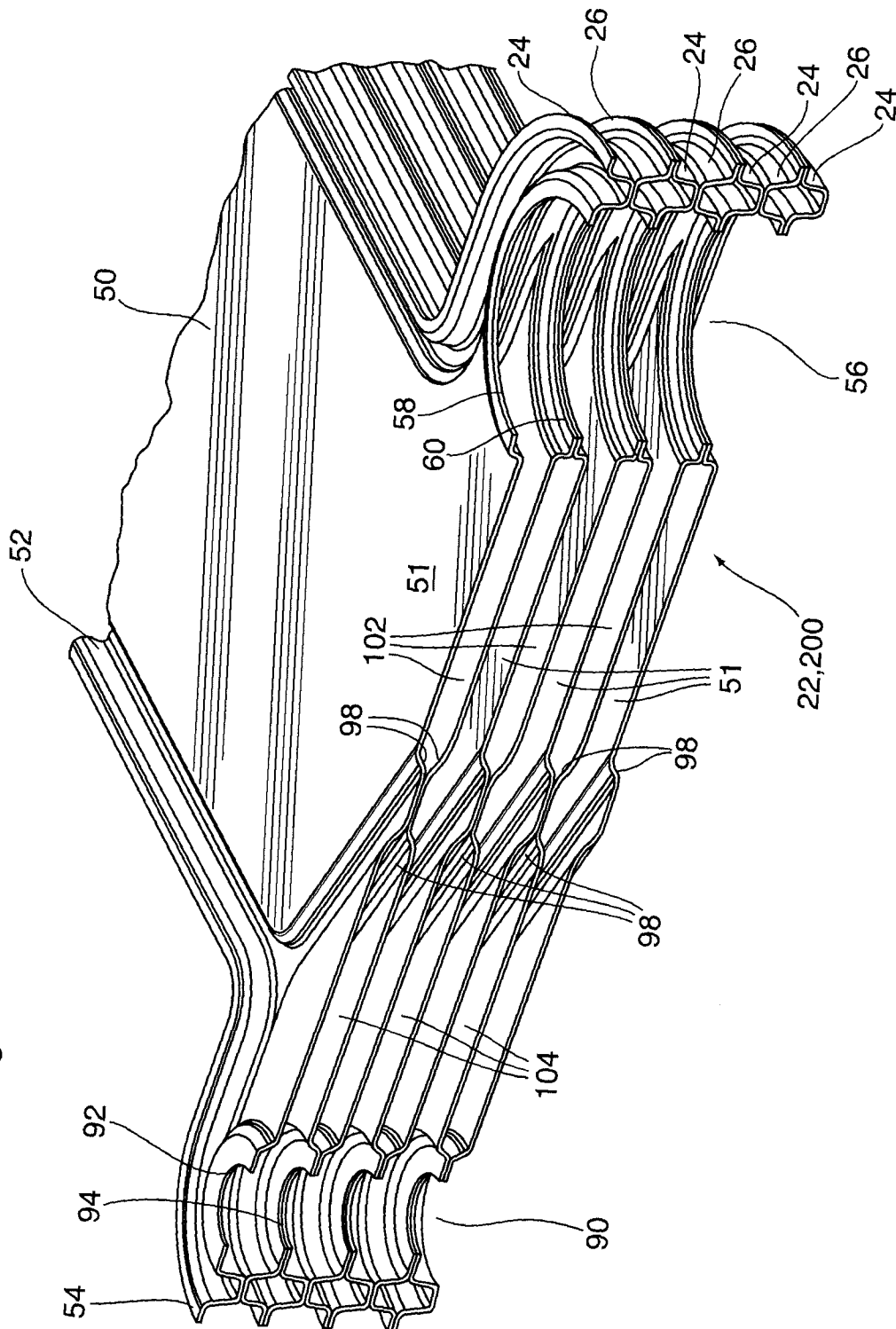
18 / 20

Fig.17



19 / 20

Fig.18



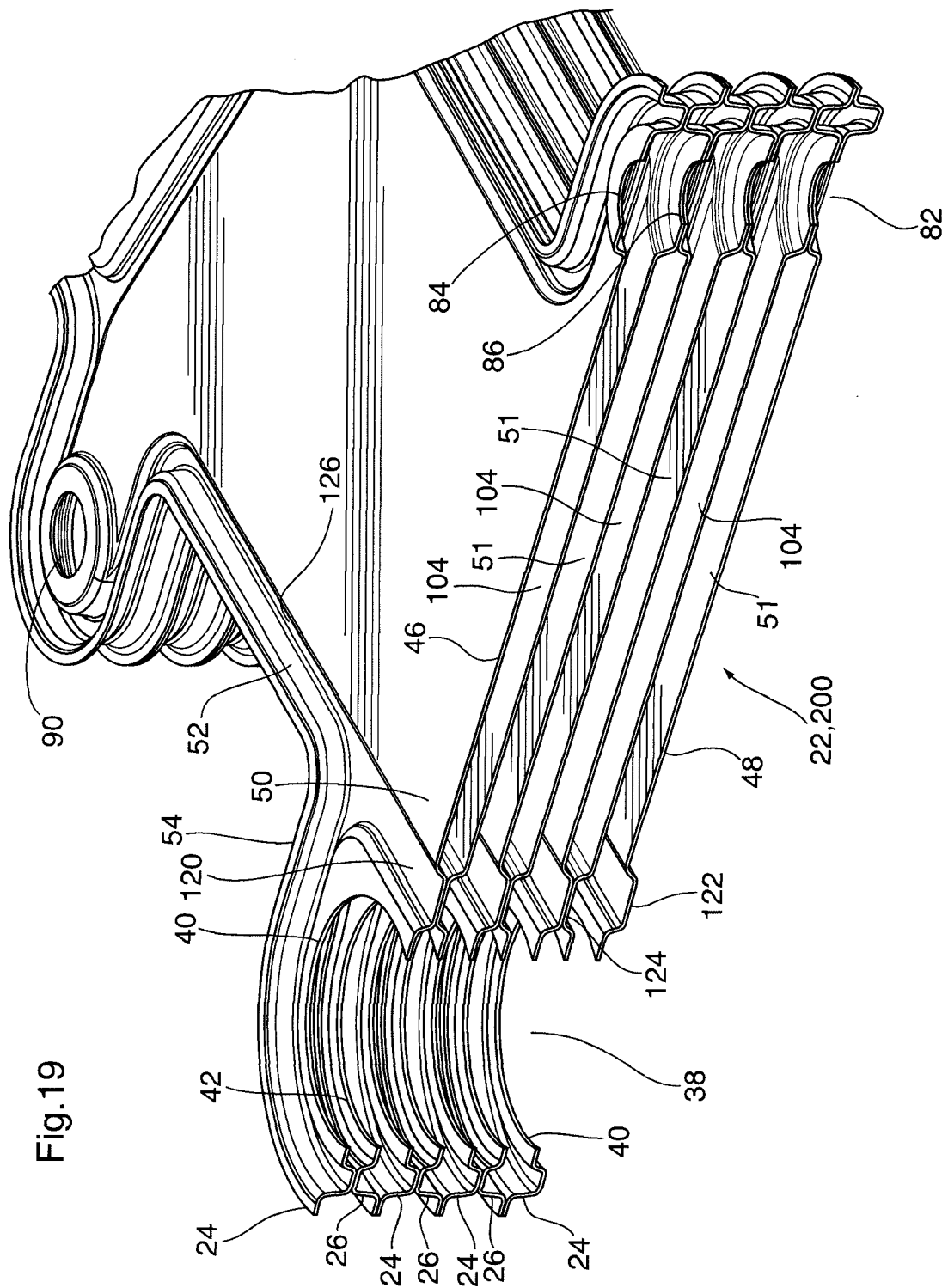


Fig. 19

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA2013/050143

<p>A. CLASSIFICATION OF SUBJECT MATTER</p> <p>IPC: H01M 8/02 (2006.01) , H01M 8/04 (2006.01)</p> <p>According to International Patent Classification (IPC) or to both national classification and IPC</p>																				
<p>B. FIELDS SEARCHED</p> <p>Minimum documentation searched (classification system followed by classification symbols)</p> <p>IPC: H01M 8/02 (2006.01) , H01M 8/04 (2006.01), F28F* (2006.01), F28D* (2006.01),</p> <p>Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched</p> <p>Electronic database(s) consulted during the international search (name of database(s) and, where practicable, search terms used)</p> <p>Epoque, Intellect, TotalPatent</p>																				
<p>C. DOCUMENTS CONSIDERED TO BE RELEVANT</p> <table border="1"> <thead> <tr> <th>Category*</th> <th>Citation of document, with indication, where appropriate, of the relevant passages</th> <th>Relevant to claim No.</th> </tr> </thead> <tbody> <tr> <td>X</td> <td>US2005/0019633 A1 (Tanaka) 27 January 2005 (27-01-2005) see whole document</td> <td>1-9, 11-15</td> </tr> <tr> <td>Y</td> <td>US7,276,308 B2 (Formanski et al.) 02 October 2007 (02-10-2007) see figure 2</td> <td>1-9, 11-15</td> </tr> <tr> <td>Y</td> <td>US2008/0081238 A1 (Becker et al.) 03 April 2008 (03-04-2008) see figure 3</td> <td>1-9, 11-15</td> </tr> <tr> <td>Y</td> <td>US2008/0102335 A1 (Skala) 01 May 2008 (01-05-2008) see whole document</td> <td>1-9, 11-15</td> </tr> <tr> <td>A</td> <td>US2008/0066895 A1 (Wegner) 20 March 2008 (20-03-2008) see whole document</td> <td>16-22, 10</td> </tr> </tbody> </table>			Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.	X	US2005/0019633 A1 (Tanaka) 27 January 2005 (27-01-2005) see whole document	1-9, 11-15	Y	US7,276,308 B2 (Formanski et al.) 02 October 2007 (02-10-2007) see figure 2	1-9, 11-15	Y	US2008/0081238 A1 (Becker et al.) 03 April 2008 (03-04-2008) see figure 3	1-9, 11-15	Y	US2008/0102335 A1 (Skala) 01 May 2008 (01-05-2008) see whole document	1-9, 11-15	A	US2008/0066895 A1 (Wegner) 20 March 2008 (20-03-2008) see whole document	16-22, 10
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.																		
X	US2005/0019633 A1 (Tanaka) 27 January 2005 (27-01-2005) see whole document	1-9, 11-15																		
Y	US7,276,308 B2 (Formanski et al.) 02 October 2007 (02-10-2007) see figure 2	1-9, 11-15																		
Y	US2008/0081238 A1 (Becker et al.) 03 April 2008 (03-04-2008) see figure 3	1-9, 11-15																		
Y	US2008/0102335 A1 (Skala) 01 May 2008 (01-05-2008) see whole document	1-9, 11-15																		
A	US2008/0066895 A1 (Wegner) 20 March 2008 (20-03-2008) see whole document	16-22, 10																		
<p>[X] Further documents are listed in the continuation of Box C. [X] See patent family annex.</p> <table border="1"> <tbody> <tr> <td>* Special categories of cited documents :</td> <td>"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</td> </tr> <tr> <td>"A" document defining the general state of the art which is not considered to be of particular relevance</td> <td>"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone</td> </tr> <tr> <td>"E" earlier application or patent but published on or after the international filing date</td> <td>"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</td> </tr> <tr> <td>"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</td> <td>"&" document member of the same patent family</td> </tr> <tr> <td>"O" document referring to an oral disclosure, use, exhibition or other means</td> <td></td> </tr> <tr> <td>"P" document published prior to the international filing date but later than the priority date claimed</td> <td></td> </tr> </tbody> </table>			* Special categories of cited documents :	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention	"A" document defining the general state of the art which is not considered to be of particular relevance	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone	"E" earlier application or patent but published on or after the international filing date	"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	"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&" document member of the same patent family	"O" document referring to an oral disclosure, use, exhibition or other means		"P" document published prior to the international filing date but later than the priority date claimed							
* Special categories of cited documents :	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention																			
"A" document defining the general state of the art which is not considered to be of particular relevance	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone																			
"E" earlier application or patent but published on or after the international filing date	"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																			
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&" document member of the same patent family																			
"O" document referring to an oral disclosure, use, exhibition or other means																				
"P" document published prior to the international filing date but later than the priority date claimed																				
<p>Date of the actual completion of the international search</p> <p>05 June 2013 (05-06-2013)</p>		<p>Date of mailing of the international search report</p> <p>07 June 2013 (07-06-2013)</p>																		
<p>Name and mailing address of the ISA/CA</p> <p>Canadian Intellectual Property Office</p> <p>Place du Portage I, C114 - 1st Floor, Box PCT</p> <p>50 Victoria Street</p> <p>Gatineau, Quebec K1A 0C9</p> <p>Facsimile No.: 001-819-953-2476</p>		<p>Authorized officer</p> <p>Laurent de Camprieux (819) 994-0249</p>																		

INTERNATIONAL SEARCH REPORTInternational application No.
PCT/CA2013/050143**Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of the first sheet)**

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons :

1. ☐ Claim Nos. :
because they relate to subject matter not required to be searched by this Authority, namely :

2. ☐ Claim Nos. :
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically :

3. ☐ Claim Nos. :
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows :

Group A - Claims 1-15 are directed to a method and system for cooling a pressurized cathode air stream in a fuel cell system, using a first charge air cooler comprising a gas-to-gas charge air cooler and a second charge air cooler, a gas-to-gas humidifier and a fuel cell stack.

Group B - Claims 16-22 are directed to a three-fluid charge air cooler comprising a plurality of plates in a plate stack having a first end and second end and a length extending from the first end to the second end and the plate stack being divided along its

1. ☒ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claim Nos. :
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claim Nos. :

Remark on Protest ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☒ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORTInternational application No.
PCT/CA2013/050143

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US2002/0026999 A1 (Wu et al.) 07 March 2002 (07-03-2002) see whole document	16-22, 10
P, A	FR 2 977 308 A1 (Naudin et al.) 04 January 2013 (04-01-2013) see whole document	16-22, 10
A	US 7,992,628 B2 (Melby et al.) 09 August 2011 (09-08-2011) see whole document	16-22, 10
A	US 2005/0095488 A1 (Formanski et al.) 05 May 2005 (05-05-2005) see figure 1	1-9, 11-15

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/CA2013/050143

Patent Document Cited in Search Report	Publication Date	Patent Family Member(s)	Publication Date
US2005019633A1	27 January 2005 (27-01-2005)	EP1501149A2 EP1501149A3 JP2005044630A	26 January 2005 (26-01-2005) 14 December 2005 (14-12-2005) 17 February 2005 (17-02-2005)
US7276308B2	02 October 2007 (02-10-2007)	AU2003294680A1 AU2003294680A8 CN1745494A CN100375326C DE10394059B4 DE10394059T5 JP2006522431A JP4773725B2 US2004151959A1 US2004151958A1 WO2004070856A2 WO2004070856A3	30 August 2004 (30-08-2004) 30 August 2004 (30-08-2004) 08 March 2006 (08-03-2006) 12 March 2008 (12-03-2008) 31 October 2012 (31-10-2012) 22 December 2005 (22-12-2005) 28 September 2006 (28-09-2006) 14 September 2011 (14-09-2011) 05 August 2004 (05-08-2004) 05 August 2004 (05-08-2004) 19 August 2004 (19-08-2004) 09 December 2004 (09-12-2004)
US2008081238A1	03 April 2008 (03-04-2008)	DE102007046056A1 US8053126B2	30 April 2008 (30-04-2008) 08 November 2011 (08-11-2011)
US2008102335A1	01 May 2008 (01-05-2008)	CN101227005A CN101227005B DE102007050415A1 JP2008108730A US8298713B2	23 July 2008 (23-07-2008) 23 June 2010 (23-06-2010) 08 May 2008 (08-05-2008) 08 May 2008 (08-05-2008) 30 October 2012 (30-10-2012)
US2008066895A1	20 March 2008 (20-03-2008)	DE102006044154A1 EP1901020A2 EP1901020A3 US8020612B2	21 May 2008 (21-05-2008) 19 March 2008 (19-03-2008) 10 April 2013 (10-04-2013) 20 September 2011 (20-09-2011)
continued on extra sheet			

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA2013/050143

US2002026999A1	07 March 2002 (07-03-2002)	AT265664T	15 May 2004 (15-05-2004)
		AT265665T	15 May 2004 (15-05-2004)
		AT278927T	15 October 2004 (15-10-2004)
		AU747036B2	09 May 2002 (09-05-2002)
		AU747149B2	09 May 2002 (09-05-2002)
		AU748688B2	13 June 2002 (13-06-2002)
		AU2528400A	25 August 2000 (25-08-2000)
		AU2528500A	25 August 2000 (25-08-2000)
		AU2652500A	25 August 2000 (25-08-2000)
		BR0008007A	20 November 2001 (20-11-2001)
		BR0008007B1	13 January 2009 (13-01-2009)
		CA2260890A1	05 August 2000 (05-08-2000)
		CA2298009A1	05 August 2000 (05-08-2000)
		CA2298009C	20 February 2007 (20-02-2007)
		CA2298116A1	05 August 2000 (05-08-2000)
		CA2298116C	16 October 2007 (16-10-2007)
		CA2298118A1	05 August 2000 (05-08-2000)
		CA2298118C	13 March 2007 (13-03-2007)
		DE60010226D1	03 June 2004 (03-06-2004)
		DE60010226T2	19 May 2005 (19-05-2005)
		DE60010227D1	03 June 2004 (03-06-2004)
		DE60010227T2	25 May 2005 (25-05-2005)
		DE60014580D1	11 November 2004 (11-11-2004)
		DE60014580T2	13 October 2005 (13-10-2005)
		EP1149264A1	31 October 2001 (31-10-2001)
		EP1149264B1	28 April 2004 (28-04-2004)
		EP1149265A1	31 October 2001 (31-10-2001)
		EP1149265B1	28 April 2004 (28-04-2004)
		EP1149266A1	31 October 2001 (31-10-2001)
		EP1149266B1	06 October 2004 (06-10-2004)
		ES2219304T3	01 December 2004 (01-12-2004)
		ES2219305T3	01 December 2004 (01-12-2004)
		JP2002536620A	29 October 2002 (29-10-2002)
		JP3524063B2	26 April 2004 (26-04-2004)
		JP2002536621A	29 October 2002 (29-10-2002)
		JP3524064B2	26 April 2004 (26-04-2004)
		JP2002536622A	29 October 2002 (29-10-2002)
		JP3524065B2	26 April 2004 (26-04-2004)
		US6199626B1	13 March 2001 (13-03-2001)
		US6244334B1	12 June 2001 (12-06-2001)
		US6340053B1	22 January 2002 (22-01-2002)
		US7051799B2	30 May 2006 (30-05-2006)
		WO0046562A1	10 August 2000 (10-08-2000)
		WO0046563A1	10 August 2000 (10-08-2000)
		WO0046564A1	10 August 2000 (10-08-2000)
FR2977308A1	04 January 2013 (04-01-2013)	None	
US7992628B2	09 August 2011 (09-08-2011)	DE102007021708A1	03 January 2008 (03-01-2008)
		DE102007021708B4	16 February 2012 (16-02-2012)
		FR2900968A1	16 November 2007 (16-11-2007)
		JP2007303812A	22 November 2007 (22-11-2007)
		US2007261815A1	15 November 2007 (15-11-2007)
US2005095488A1	05 May 2005 (05-05-2005)	DE102004051359A1	09 June 2005 (09-06-2005)
		DE102004051359B4	25 March 2010 (25-03-2010)
		JP2005135910A	26 May 2005 (26-05-2005)
		JP4584672B2	24 November 2010 (24-11-2010)
		US7344787B2	18 March 2008 (18-03-2008)