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(54) Title: RECUPERATIVE HEAT EXCHANGER AND METHOD OF OPERATING THE SAME

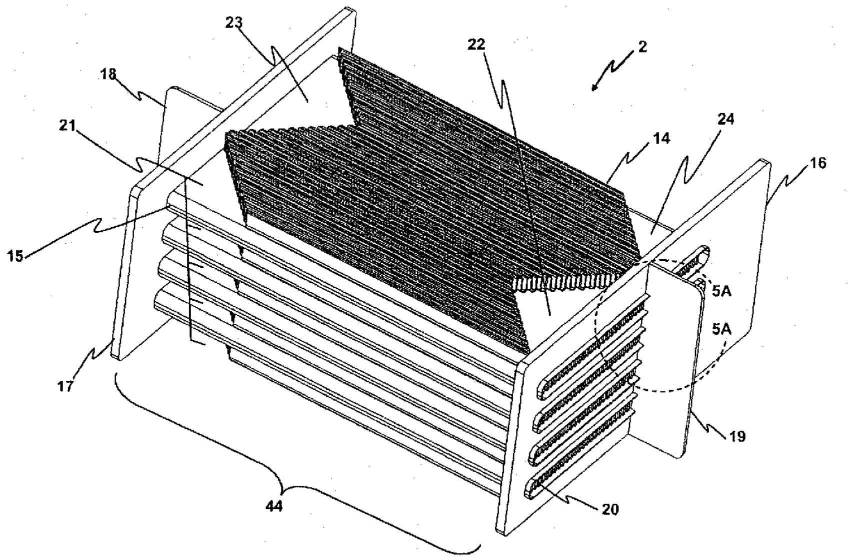

FIG. 5

(57) **Abstract**: A recuperative heat exchanger including a plate at least partially defining a first flow path. A portion of the first flow path can extend between first and second edges of the plate. The heat exchanger can also include a second flow path including a plurality of channels at least partially defined by a plurality of fins supported on a surface of the plate. The plurality of channels can have inlet ends proximate the first edge of the plate and exit ends proximate the second edge of the plate. The inlet ends of the channels can be spaced at varying distances from the first edge of the plate.

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RECUPERATIVE HEAT EXCHANGER AND METHOD OF OPERATING THE SAME

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This applications claims priority to U.S. Provisional Patent Application No. 60/992,841, filed on December 6, 2007, the contents of which are hereby incorporated by reference.

FIELD OF THE INVENTION

[0002] The present invention relates to heat exchangers in general and in more particular applications, to recuperative heat exchangers which find many uses in industry, including in fuel cell systems.

BACKGROUND

[0003] A recuperative heat exchanger, or recuperator, is used to optimize the overall system efficiency of a high temperature application, such as a gas turbine or a high temperature fuel cell system, by heating a low temperature incoming air stream to a temperature closer to the desired process operating temperature via the transfer of thermal energy from a high temperature process waste stream of exhaust gas or air. Such a heat exchanger allows for the efficient transfer of heat from the hot stream to the cold stream while maintaining isolation of the two streams from each other. A compact recuperator is usually desirable in order to simplify the packaging of the recuperator into the system, and in order to reduce the material costs of the device. It is also typically a principal object of such a heat exchanger to provide for high heat exchanger effectiveness in order to maximize the degree to which the heat is recuperated.

[0004] Heat exchanger effectiveness is defined as the ratio between the actual rate at which heat is transferred between the two fluids in a heat exchanger and the maximum possible heat transfer rate. The maximum possible heat transfer rate is achieved when the exit temperature of the fluid with the lower heat capacity is made to be equal to the entering temperature of the other fluid, and can theoretically be achieved in a heat exchanger of infinite length with the fluids passing through it in a counter-flow orientation. For all practical heat exchangers the effectiveness will be less than one.

[0005] Recuperative heat exchangers can take many forms, but topologies commonly used exhibit multiple parallel flow paths for each fluid, with thin metallic separator surfaces located between the hot and cold streams. The surface area of these separator surfaces is maximized in order to maximize the heat transfer capability of the recuperator, usually by convolution of the primary surface or by the addition of secondary surfaces that are metallurgically bonded to the primary surface, as in a plate and fin heat exchanger. The orientation of the flows through the recuperator can be single or multiple pass cross-flow, or counter-flow for applications requiring greater heat exchanger effectiveness.

[0006] Typical heat exchangers employed as recuperators are of a plate-and-frame design, wherein a large plurality of low-profile flow channels, often with heat transfer surface augmentation features, are assembled into a stack and are manifolded so that the cold and hot gas streams flow in heat exchange relationship in alternating flow channels. While such a heat exchanger design can achieve a high degree of compactness, it will typically require a large number of plates to construct the many flow channels, thereby also requiring sealing of a substantial joint length along the edges of the plates. This increases the possibility of leaks occurring in the heat exchanger. Furthermore, the production of plates suitable for such an application requires significant tooling investment, making it a non-preferable design for low-volume applications.

[0007] An alternative approach that attempts to reduce the cost and complexity of such a recuperative heat exchanger can be found in US patent 7,255,157 by Richardson. The Richardson patent describes a recuperative heat exchanger using a plurality of corrugated tubes to convey a first gas through the heat exchanger while flowing a second gas over the tubes so that heat can be transferred between the flows through the tube walls. While there are certain advantages to the heat exchanger design of Richardson, the enabled embodiments all represent a heat exchanger that operates as a shell-and-tube heat exchanger with one shell pass and a multiple of two tube passes. It is well known in the art of heat exchangers that such a heat exchanger, when operated with fluids having nearly equal heat capacities (as is typical in a recuperative heat exchange application), has a maximum achievable heat transfer effectiveness of approximately 60%. While such effectiveness may be acceptable for some recuperative heat exchanger applications, there are many applications where a higher effectiveness can be either beneficial or necessary for proper operation of the system. Thus there is still room for improvement.

SUMMARY

[0008] In one embodiment, the present invention provides a recuperative heat exchanger that includes a plurality of heat exchange passes, wherein each pass comprises a plurality of first flow channels to direct a first fluid flow there-through, and a plurality of second flow channels to direct a second fluid flow there-through in a direction counter to the flow direction of the first fluid flow. Also included are a first inlet tank configured to receive the first fluid flow into the heat exchanger and to convey the first fluid into the plurality of first flow channels comprising the first pass of the heat exchanger; and a first exit tank configured to receive the first fluid flow from the plurality of first flow channels comprising the last pass of the heat exchanger and to convey the first fluid flow out of the heat exchanger; and one or more intermediate tanks configured to receive the first fluid flow from the plurality of first flow channels comprising one pass of the heat exchanger and to convey the first fluid flow to the plurality of first flow channels comprising another pass of the heat exchanger; and a second inlet tank configured to receive the second fluid flow into the heat exchanger and to convey the second fluid into the plurality of second flow channels comprising the last pass of the heat exchanger; and a second exit tank configured to receive the second fluid flow from the plurality of second flow channels comprising the first pass of the heat exchanger and to convey the second fluid flow out of the heat exchanger; and a plurality of flow baffles configured to direct the second fluid flow exiting a first second flow channel in one pass of the heat exchanger into a second flow channel in another pass of the heat exchanger.

[0009] In some embodiments, the recuperative heat exchanger comprises a plurality of thermally conductive walls, each wall providing a portion of the flow boundary for at least one of the plurality of first flow channels and at least one of the plurality of second flow channels in each of the heat exchange passes, and allowing for the transfer of heat between the first fluid flow and the second fluid flow.

[0010] In some embodiments, heat transfer enhancement features are attached via a metallurgical bond to the plurality of thermally conductive walls in order to improve the rate of heat transfer through the walls.

[0011] In some embodiments, the heat transfer enhancement features comprise a corrugated fin structure.

[0012] In some embodiments, the plurality of flow baffles comprises heat transfer enhancement features.

[0013] In some embodiments, the invention provides a method of operating a heat exchanger including acts of directing a fluid sequentially through first and second passes of a first flow path located on one side of a plate, directing an other fluid sequentially through first and second passes of a second flow path located on an opposing side of the plate, the second flow path being generally counter to the first flow path, transferring heat through the plate between the fluid traveling along the first pass of the first flow path and the other fluid traveling along the second pass of the second flow path, transferring heat through the plate between the fluid traveling along the second pass of the first flow path and the other fluid traveling along the first pass of the second flow path, and transferring heat through the plate between the fluid traveling along the first pass of the first flow path and the other fluid traveling along the first pass of the second flow path.

[0014] The invention also provides a method of transferring heat to a fluid traveling through a recuperative heat exchanger including the acts of directing the fluid sequentially through first and second passes of a first flow path, the first and second passes extending through a tube, directing the fluid sequentially through first and second passes of a second flow path at least partially defined by an exterior surface of the tube, transferring heat through the tube between the fluid traveling along the first pass of the first flow path and the fluid traveling along the second pass of the second flow path, and transferring heat through the tube between the fluid traveling along the second pass of the first flow path and the fluid traveling along the first pass of the second flow path. The method can also include the act of transferring heat through the tube between the fluid traveling along the first pass of the first flow path and the fluid traveling along the first pass of the second flow path. In some embodiments, the method can include the act of transferring heat though the tube along a width of the tube in a direction substantially perpendicular to the first pass of the first flow path.

[0015] The invention also provides a recuperative heat exchanger including a plate at least partially defining a first flow path. A portion of the first flow path can extend between first and second edges of the plate. The heat exchanger can also include a second flow path including a plurality of channels at least partially defined by a plurality of fins supported on a surface of the plate. The plurality of channels can have inlet ends proximate the first edge of the plate and exit ends proximate the second edge of the plate. The inlet ends of the channels can be spaced at varying distances from the first edge of the plate.

[0016] Other aspects of the invention will become apparent by consideration of the detailed description and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] FIG. 1 is a perspective view of a recuperative heat exchanger embodying the present invention.

[0018] FIG. 2 is a schematic view of the flow path of a first fluid passing through the heat exchanger of FIG. 1.

[0019] FIG. 3 is a schematic view of the flow path of a second fluid passing through the heat exchanger of FIG. 1.

[0020] FIG. 4 is an exploded isometric view of the recuperative heat exchanger of FIG. 1.

[0021] FIG. 5 is a perspective view of a heat exchanger core from the heat exchanger of FIG. 1.

[0022] FIG. 5A is an enlarged partial view taken from line 5A-5A of FIG. 5.

[0023] FIG. 6 is a partial plan view of a tube and insert as used in the heat exchanger of FIG. 1.

[0024] FIG. 7 is a perspective view of a shell-side convoluted fin section as used in the heat exchanger of FIG. 1.

[0025] FIG. 8 is a graph of the calculated bulk fluid temperature profiles in a heat exchanger embodying the present invention at design conditions.

[0026] FIG. 9 is a graph similar to that of FIG. 8 but with each fluid at 40% of the design flow rate.

[0027] FIG. 10 is a graph similar to that of FIG. 8 but with each fluid at 70% of the design flow rate.

DETAILED DESCRIPTION

[0028] Before any embodiments of the invention are explained in detail, it is to be understood that the invention is not limited in its application to the details of construction and the arrangement of components set forth in the following description or illustrated in the following drawings. The invention is capable of other embodiments and of being practiced or of being carried out in various ways. Also, it is to be understood that the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. The use of "including," "comprising," or "having" and variations thereof herein is meant to encompass the items listed thereafter and equivalents thereof as well as additional items. Unless specified or limited otherwise, the terms "mounted," "connected," "supported," and "coupled" and variations thereof are used broadly and encompass both direct and indirect mountings, connections, supports, and couplings. Further, "connected" and "coupled" are not restricted to physical or mechanical connections or couplings.

[0029] FIG. 1 shows a heat exchanger 1 embodying the present invention. The heat exchanger 1 includes a first inlet port 10 to receive a first fluid flow at a first end of the heat exchanger 1 and a second inlet port 12 to receive a second fluid flow at a second end of the heat exchanger, the second end of the heat exchanger 1 being located opposite the first end of the heat exchanger 1. The heat exchanger 1 further includes a first exit port 11 located at the second end of the heat exchanger 1 to remove the first fluid therefrom, and a second exit port 13 located at the first end of the heat exchanger 1 to remove the second fluid therefrom. A first fluid passes through the heat exchanger 1 from first fluid inlet port 10 to first fluid exit port 11 in an overall counter-flow direction to a second fluid that passes through the heat exchanger 1 from second fluid inlet port 12 to second fluid exit port 13.

[0030] The heat exchanger 1 embodying the present invention further includes a heat exchange region 44, depicted diagrammatically in FIG. 2 and FIG. 3. With specific reference to FIG. 2, the flow path of the first fluid through the heat exchange region 44 includes: a first heat exchange pass 41 for the first fluid; a second heat exchange pass 42 for the first fluid located adjacent, and flowing in a direction opposite to, the first heat exchange pass 41; and a third heat exchange pass 43 for the first fluid located adjacent, and flowing in a direction opposite to, the second heat exchange pass 42. The heat exchanger 1 further includes: a first fluid inlet plenum 37 in fluid communication with the inlet of the first heat exchange pass 41 for the first fluid; a first intermediate plenum 38 for the first fluid, the plenum 38 being in fluid communication with the exit of the first heat exchange pass 41 for the first fluid and with the inlet of the second heat exchange pass 42 for the first fluid; a second intermediate plenum 39 for the first fluid, the plenum 39 being in fluid communication with the exit of the second heat exchange pass 42 for the first fluid and with the inlet of the third heat exchange pass 43 for the first fluid; and a first fluid exit plenum 40 in fluid communication with the exit of the third heat exchange pass 43 for the first fluid.

[0031] Turning now to FIG. 3, the flow path of the second fluid through the heat exchange region 44 comprises: a first heat exchange pass 34 for the second fluid; a second heat exchange pass 35 for the second fluid located adjacent, and flowing in a direction opposite to, the first heat exchange pass 34; and a third heat exchange pass 36 for the second fluid located adjacent, and flowing in a direction opposite to, the second heat exchange pass 35. The heat exchanger 1 further includes: an inlet manifold 21 in fluid communication with the inlet of the first heat exchange pass 34 for the second fluid; a first intermediate manifold 22 for the second fluid, the manifold 22 being in fluid communication with the exit of the first heat exchange pass 34 of the second fluid and with the inlet of the second heat exchange pass 35 for the second fluid; a second intermediate manifold 23 for the second fluid, the manifold 23 being in fluid communication with the exit of the second heat exchange pass 35 of the second fluid and with the inlet of the third heat exchange pass 36 for the second fluid; an exit manifold 24 in fluid communication with the exit of the third heat exchange pass 36 for the second fluid; a second fluid inlet plenum 45 in fluid communication with the inlet manifold 21; and a second fluid exit plenum 46 in fluid communication with the exit manifold 24.

[0032] In the illustrated embodiment, the first heat exchange pass 41 for the first fluid and the third heat exchange pass 36 for the second fluid will be in heat exchange relation with one another, and will flow in opposing directions, thus enabling counter-flow heat exchange between the fluids in those passes. In a similar fashion, such an embodiment would enable counter-flow heat exchange between the fluid in the second heat exchange pass 42 for the first fluid and the fluid in the second heat exchange pass 35 for the second fluid, and between the fluid in the third heat exchange pass 43 for the first fluid and the fluid in the first heat exchange pass 34 for the second fluid.

[0033] Turning now to FIG. 4, several of the components comprising a heat exchanger 1 embodying the present invention will be described. The heat exchanger 1 comprises: a heat exchanger core 2 comprising the heat exchange region 44; a first fluid inlet tank 3 providing the first fluid inlet port 10 and in part comprising the first fluid inlet plenum 37; a first intermediate tank 5 in part comprising the first intermediate plenum 38 for the first fluid; a second intermediate tank 6 in part comprising the second intermediate plenum 39 for the first fluid; a first fluid exit tank 4 providing the first fluid exit port 11 and in part comprising the first fluid exit plenum 40; a second fluid inlet tank 7 providing the second fluid inlet port 12 and comprising the second fluid exit plenum 45; a second fluid exit tank 8 providing the second fluid exit port 13 and in part comprising the second fluid exit plenum 46; and outer shell components 9a and 9b.

[0034] The heat exchanger core 2 will now be described in greater detail with specific reference to Figs. 5-7. The core 2 comprises a first header plate 16, a second header plate 17 parallel to the first header plate 16 and spaced some distance away to define a heat exchange region 44 between the header plates, and a plurality of flattened tubes 15 spanning the distance between the header plates 16 and 17 and penetrating through openings in the header plates 16 and 17 to provide a fluid conduit through the heat exchange region 44. In the illustrated construction, the ends of the tubes 15 are sealingly attached to the header plates 16 and 17, such as by welding or brazing. However, other coupling mechanisms fall within the scope of the invention. The plurality of tubes 15 contains a plurality of convoluted inserts 20, best seen in FIG. 6. The inserts 20 are comprised of a plurality of fins 26 and fin crests 27, the fin crests 27 serving to connect adjacent instances of the fins 26. Although rounded crests are shown in the accompanying drawings, it should be readily appreciated by those having ordinary skill in the art of heat exchangers that the fin crests can also be of a flat, squared-off shape. The fins 26 can be approximately perpendicular to planar plates or walls 25 of the tubes 15, and the convoluted inserts 20 may preferably be sized so that the fin crests 27 can be bonded to the walls 25, such as by brazing. In this manner, the convoluted inserts 20 and tubes 15 comprise a plurality of parallel flow channels 28 and provide a large surface area for convective heat transfer to or from a fluid passing through the channels. The plurality of flow channels 28 comprises the heat exchange passes for the first fluid.

[0035] In the illustrated construction, the heat exchanger core 2 further comprises of a plurality of shell-side convoluted fin sections 14. Each shell-side convoluted fin section 14 comprises a plurality of fins 32 and fin crests 33, the fin crests 33 serving to connect adjacent instances of the fins 32. Although rounded crests are shown in the accompanying drawings, it should be readily appreciated by those having ordinary skill in the art of heat exchangers that the fin crests can also be of a flat, squared-off shape. A convoluted fin section 14 is located on either side of each of the flattened tubes 15, and the fin crests 33 are bonded to the walls 25 of the tubes 15, such as by brazing. In a preferred embodiment of the heat exchanger 1, the exposed fin crests on the outermost instances of the shell-side convoluted fin sections 14 are in contact with the adjacent walls of the outer shell components 9a and 9b. In some embodiments the fin crests may be bonded to the walls, such as by brazing. In this manner, the shell-side convoluted fin sections 14, tubes 15, and outer shell components 9a and 9b comprise a plurality of parallel flow channels 29 and provide a large surface area for convective heat transfer to or from a fluid passing through the channels. The plurality of flow channels 29 comprises the heat exchange passes for the second fluid.

[0036] In the illustrated construction, the end faces of each shell-side convoluted fin section 14 are of a sawtooth shape when viewed from a direction perpendicular to the planar walls 25 of the flattened tubes 15. This sawtooth profile creates: a triangle-shaped inlet manifold 21 which is in fluid communication with the second fluid inlet plenum 45 and a first plurality of the flow channels 29 whose inlets are aligned in a first common plane 30 and whose outlets are aligned in a second common plane 31; a triangle-shaped first intermediate manifold 22 which is in fluid communication with the first plurality of the flow channels 29 and with a second plurality of the flow channels 29 whose inlets are aligned in a third common plane 47 and whose outlets are aligned in a fourth common plane 48; a triangle-shaped second intermediate manifold 23 which is in fluid communication with the second plurality of the flow channels 29 and with a third plurality of the flow channels 29 whose inlets are aligned in a fifth common plane 49 and whose outlets are aligned in a sixth common plane 50; and a triangle-shaped exit manifold 24 which is in fluid communication with the third plurality of the flow channels 29 and with the second fluid exit plenum 46. Accordingly, the first plurality of the channels 29 at least partially define the first pass 34 of the second fluid, the second plurality of the channels 29 at least partially define the second pass 35 of the second fluid and the third plurality of the channels 29 at least partially define the third pass 36 of the second fluid. It is to be understood that other constructions of the convoluted fin section 14 also fall within the scope of the invention. Particularly, the end faces of each shell-side convoluted fin section 14 may define shapes other than the above described sawtooth profile (e.g., wave-like and/or arcuate profiles).

[0037] In the illustrated construction, the heat exchanger core 2 includes a first flow baffle 18 connected to the second header plate 17 in order to separate the fluid in the first intermediate plenum 38 from the fluid in the first fluid exit plenum 40, and a second flow baffle 19 connected to the first header plate 16 in order to separate the fluid in the first fluid inlet plenum 37 from the fluid in the second intermediate plenum 39. As best seen in Figs. 5 and 5A, the flow baffles 18 and 19 have a plurality of slots 51 to accommodate the ends of the tubes 15 standing proud of the surfaces of the header plates 16 and 17. The flow baffle tabs 52 between the slots 51 directly abut the ends of the convoluted inserts 20. In the illustrated construction, the first fluid inlet tank 3, first header plate 16, and second flow baffle 19 at least partially define a first fluid inlet plenum 37 which is in fluid communication with a first plurality of the flow channels 28. In addition, the first intermediate tank 5, second header plate 17, and first flow baffle 18 at least partially define a first intermediate plenum 38 which is in fluid communication with the first plurality of the flow channels 28 and with a second plurality of the flow channels 28. Further, the second intermediate tank 6, first header plate 16 and second flow baffle 19 at least partially define a second intermediate plenum 39 which is in fluid communication with the second plurality of the flow channels 28 and with a third plurality of the flow channels 28; and the first fluid exit tank 4, second header plate 17 and first flow baffle 18 at least partially define a first fluid exit plenum 40 which is in fluid communication with the third plurality of the flow channels 28. The first plurality of the channels 28 at least partially define the first pass 41 of the first fluid, the second plurality of the channels 28 at least partially define the second pass 42 of the first fluid, and the third plurality of the channels 28 at least partially define the third pass 43 of the first fluid.

[0038] While the invention has been described by reference to the specific construction illustrated in Figs. 1-7, it should be understood that the invention is not intended to be limited by the description of such construction. It should be particularly understood that the construction embodying the invention (as illustrated in Figs. 1-7) includes three passes for ease of description and therefore other constructions can include more or fewer passes as may be desirable or necessary based on particular parameters.

[0039] The invention, as described with reference to Figs. 1-7, for example, meets the objective of providing a compact recuperative heat exchanger capable of high heat exchanger effectiveness while also providing reduced cost and complexity over previous designs. The use of multiple passes within the heat exchanger enables a long counter-flow heat exchange length without requiring a long and narrow package, thereby allowing the heat exchanger to be packaged into a smaller space in a system requiring such a recuperator. Complexity is reduced by using only a few tubes and achieving multiple flow passes within each tube, thereby minimizing the number of fluid sealing joints. Furthermore, the heat exchange core as shown in the described embodiments can be manufactured using a furnace brazing operation, thereby reducing cost of manufacture. In addition, the use of heat transfer augmentation surfaces such as flow baffling features for the second fluid results in a parts count reduction with inherent cost benefits.

[0040] Numerical modeling of a recuperative heat exchanger according to the present invention has been used to determine the achievable heat exchanger effectiveness. FIG. 8 shows the resulting fluid temperature profiles within the heat exchanger when it is operated at the design conditions. At these conditions, the first fluid is dry air with a mass flow rate of 4.00 grams per second entering the heat exchanger at a temperature of 148°C, and the second fluid is dry air with a mass flow rate of 4.02 grams per second entering the heat exchanger at a temperature of 533°C. The numerical modeling results predict a heat exchanger effectiveness of 78%, thus exceeding what would be possible with a multiple-pass cross-flow design.

[0041] The reader skilled in the art will recognize that the use of a continuous tube wall within multiple passes of a counter-flow heat exchanger has the potential to result in considerable lateral heat spreading in the tube wall from a hotter pass to a colder pass, and that this can cause a reduction in heat transfer effectiveness. The numerical modeling described above incorporates this effect, and the results shown in FIG. 8 demonstrate that the impact of lateral heat spreading in the tube wall can be overcome with appropriate heat transfer design. In other words, the heat transfer capability of the described embodiment is sufficiently high such that a desired heat exchanger effectiveness can be achieved even though some lateral heat spreading occurs within the tube walls.

[0042] In the course of performing further numerical modeling, the inventors have determined that certain benefits can actually be realized from the lateral heat spreading effect. Within applications incorporating a recuperative heat exchanger, it is often desirable to have the effectiveness of the heat exchanger not vary greatly when the flow rates are reduced from the design conditions, an operating state commonly referred to as "turndown". In a typical counter-flow heat exchanger the effectiveness at turndown will increase substantially due to the reduction in heat capacity of the flow streams. It is not uncommon for such applications to require the addition of a flow bypass circuit, which allows for a portion of one of the fluids to bypass the heat exchanger and rejoin the non-bypassed flow downstream of the heat exchanger in order to control the temperature of the resulting flow. Such a bypass requires both additional hardware and control schemes, thus adding cost and complexity to the system.

[0043] The inventors have determined that the lateral heat spreading effects become more pronounced at turndown conditions, and that the resulting reduction in heat exchanger effectiveness can counteract the increase in heat exchanger effectiveness that naturally results from operating with reduced flow rates. This effect can be seen in Figs. 9 and 10, which shows the results of a numerical modeling case identical to the previously mentioned case except that both flow rates were reduced to a percentage of their original values. The graph of FIG. 9 shows the case where both flow rates were reduced to 40% of the original value. It can be seen from the graph that the lateral heat spreading effects at these flow rates results in essentially no net heat transfer between the two fluids in the second pass of the heat exchanger, thereby effectively shortening the total heat exchange length. The heat exchanger effectiveness as calculated from the results for this case is 79%, which is almost identical to that calculated in the design condition case. The graph of FIG. 10, which shows the case where both flow rates were reduced to 70% of the original value shows similar results. The heat spreading effect is less pronounced than was seen in the graph of FIG. 9, as is to be expected since the magnitude of the flow turndown is less. However, the heat exchanger effectiveness as calculated from the results for this case is also 79%.

[0044] This ability of achieving high heat exchanger effectiveness that stays nearly constant over turndown provides significant advantages over previous recuperative heat exchanger designs in that the bypass hardware and control schemes can be eliminated. The inventors realize that in some applications it may still be desirable to incorporate the ability to bypass a portion of one of the flows in order to more precisely control the resulting temperature. In one alternative embodiment of the invention contemplated by the inventors, a portion of the incoming first fluid may be bypassed to another inlet port for the first fluid incorporated into either the first intermediate tank 5 or the second intermediate tank 6 as shown in FIG. 4, or another intermediate tank in an embodiment having more than three passes. In this manner a portion of the first fluid flow can bypass one or more passes of the heat exchanger in order to more accurately control the resulting fluid temperatures.

[0045] The construction embodying the invention as described above and illustrated in the figures is presented by way of example only and is not intended as a limitation upon the concepts and principles of the present invention. As such, it will be appreciated by one having ordinary skill in the art that various changes in the elements and their configuration and arrangement are possible without departing from the spirit and scope of the present invention.

CLAIMS

What is claimed is:

1. A method of operating a heat exchanger, the method comprising the acts of:

directing a fluid sequentially through first and second passes of a first flow path located on one side of a plate;

directing an other fluid sequentially through first and second passes of a second flow path located on an opposing side of the plate, the second flow path being generally counter to the first flow path;

transferring heat through the plate between the fluid traveling along the first pass of the first flow path and the other fluid traveling along the second pass of the second flow path;

transferring heat through the plate between the fluid traveling along the second pass of the first flow path and the other fluid traveling along the first pass of the second flow path; and

transferring heat through the plate between the fluid traveling along the first pass of the first flow path and the other fluid traveling along the first pass of the second flow path.

2. The method of claim 1, wherein the plate forms a portion of a tube, and wherein the act of transferring heat through the plate between the fluid traveling along the first pass of the first flow path and the other fluid traveling along the first pass of the second flow path includes transferring heat through the tube along a width of the tube in a direction substantially perpendicular to the first pass of the first flow path.

3. The method of claim 1, wherein the plate at least partially defines a heat exchanger body, and wherein directing the other fluid sequentially through the first and second passes of the second flow path includes directing the other fluid through a plenum connecting the first and second passes of the second flow path and positioned interior of an outer perimeter of the body.

4. The method of claim 3, wherein a plurality of fins are supported on the opposing side of the plate, and wherein directing the other fluid through the plenum includes directing the other fluid past ends of the plurality of fins, the ends of the plurality of fins being staggered with respect to the outer perimeter of the body.

5. The method of claim 1, wherein directing the other fluid sequentially through the first and second passes of the second flow path includes directing the other fluid past outer edges of a plurality of fins supported on the opposing side of the plate, the outer ends being oriented along a line which is non-parallel and non-perpendicular to an outer edge of the plate.

6. A method of transferring heat to a fluid traveling through a recuperative heat exchanger, the method comprising the acts of:

directing the fluid sequentially through first and second passes of a first flow path, the first and second passes extending through a tube;

directing the fluid sequentially through first and second passes of a second flow path at least partially defined by an exterior surface of the tube;

transferring heat through the tube between the fluid traveling along the first pass of the first flow path and the fluid traveling along the second pass of the second flow path;

transferring heat through the tube between the fluid traveling along the second pass of the first flow path and the fluid traveling along the first pass of the second flow path; and

transferring heat through the tube between the fluid traveling along the first pass of the first flow path and the fluid traveling along the first pass of the second flow path.

wherein transferring heat through the tube from the fluid traveling along the first pass of the first flow path to fluid traveling along the second pass of the first flow path includes transferring heat though the tube along a width of the tube in a direction substantially perpendicular to the first pass of the first flow path.

7. The method of claim 6, wherein directing the fluid sequentially through the first and second passes of the second flow path includes directing the fluid through a plenum connecting the first and second passes of the second flow path and positioned interior of an outer-most end of the tube.

8. The method of claim 7, wherein directing the fluid sequentially through first and second passes of the second flow path includes directing the fluid across a plurality of fins supported on the exterior surface of the tube, and wherein directing the fluid through the plenum includes directing the fluid past ends of the plurality of fins, the ends of the plurality of fins being staggered with respect to an open end of the tube.

9. The method of claim 8, wherein directing the fluid across the plurality of fins supported on the exterior surface of the tube, includes directing the fluid across outer edges of the plurality of fins, the outer edges being oriented along a line which is non-parallel and non-perpendicular to an outer edge of the plate.

10. A recuperative heat exchanger comprising:

a plate at least partially defining a first flow path, the plate comprising a first edge and a second edge, a portion of the first flow path extending between the first edge and the second edge; and

a second flow path comprising a plurality of channels at least partially defined by a plurality of fins supported on a surface of the plate, the plurality of channels having inlet ends proximate the first edge of the plate and exit ends proximate the second edge of the plate;

wherein the inlet ends of the channels are spaced varying distances from the first edge of the plate.

11. The recuperative heat exchanger of claim 10, wherein the exit ends of said channels are spaced varying distances from the second edge of the plate.

12. The recuperative heat exchanger of claim 10, wherein the second flow path further comprises:

a second plurality of channels at least partially defined by a second plurality of fins supported on a surface of the plate, the second plurality of channels having inlet ends proximate the second edge of the plate and exit ends proximate the first edge of the plate;

wherein the exit ends of the second plurality of channels are spaced varying distances from the first edge of the plate.

13. The recuperative heat exchanger of claim 12, further comprising a plenum at least partially defined by the plate and connecting the inlet ends of the first plurality of channels and the exit ends of the second plurality of channels.

14. The recuperative heat exchanger of claim 13, wherein the plate and the first and second plurality of fins together at least partially define a heat exchanger body, and wherein the plenum connecting the first plurality of channels and the second plurality of channels is positioned interior of an outer perimeter of the body.

15. The recuperative heat exchanger of claim 13, wherein the plenum has a generally triangular configuration.

16. The recuperative heat exchanger of claim 10, wherein the exit ends of the channels are spaced at varying distances from the second edge of the plate.

17. The recuperative heat exchanger of claim 10, wherein the second flow path is generally counter to the first flow path.

18. The recuperative heat exchanger of claim 10, wherein the plate forms a portion of a tube.

19. The recuperative heat exchanger of claim 10, wherein the inlet ends of the fins are arranged along a line which is non-parallel and non-perpendicular to the first edge of the plate.

20. The recuperative heat exchanger of claim 19, wherein the inlet ends of the fins are arranged along a saw tooth-shaped line.

21. The recuperative heat exchanger of claim 10, wherein adjacent channels have substantially equal lengths measured between the inlet and exit ends.

22. The recuperative heat exchanger of claim 10, wherein the portion of the first flow path is a first portion, and wherein a second portion of the first flow path extends between the first edge and the second edge in a direction opposite to the first portion.

23. The recuperative heat exchanger of claim 22, wherein the first portion of the first flow path is in heat exchange relation with ones of the plurality of channels defining a first pass of the second flow path and the second flow path is in heat exchange relation with others of the plurality of channels defining a second pass of the second flow path, the first pass of the second flow path being counter to the second pass of the second flow path.

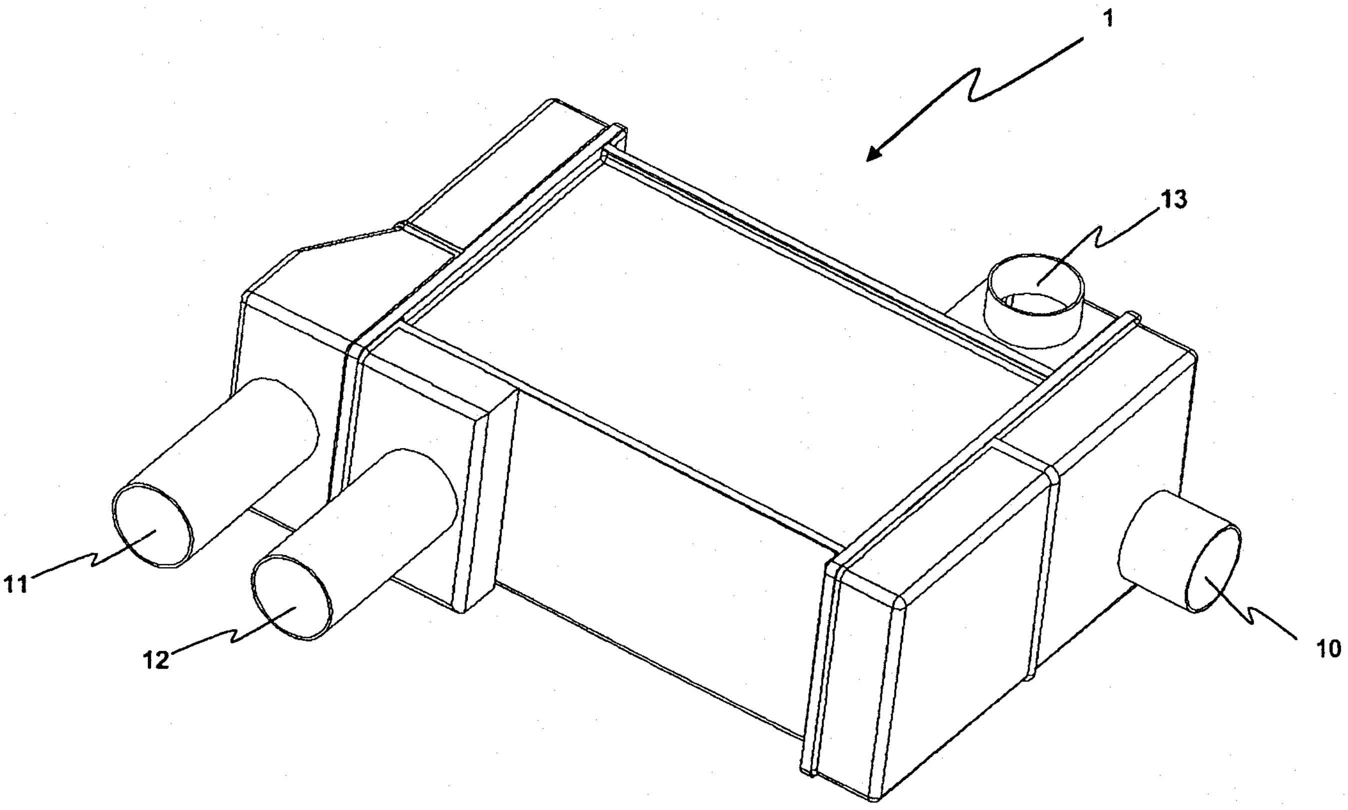


FIG. 1

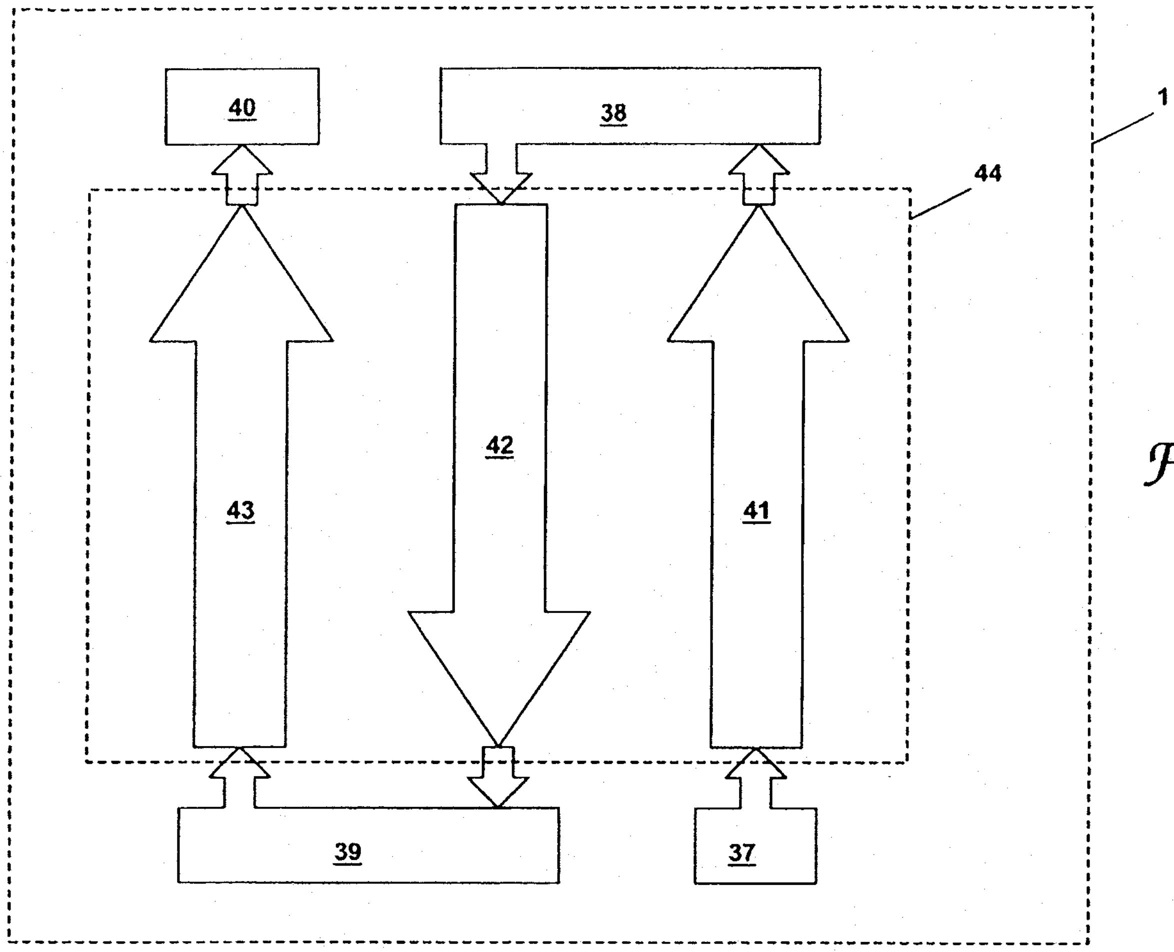


FIG. 2

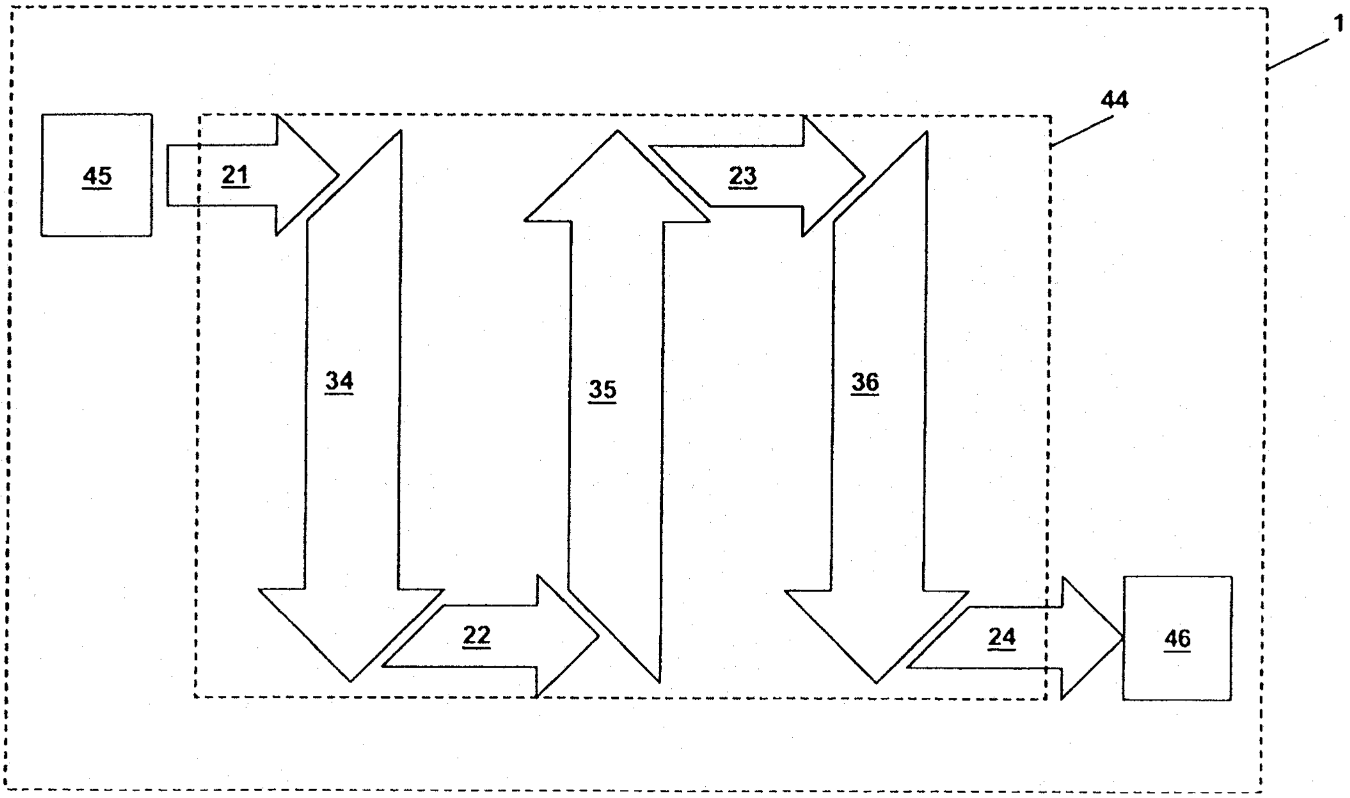


FIG. 3

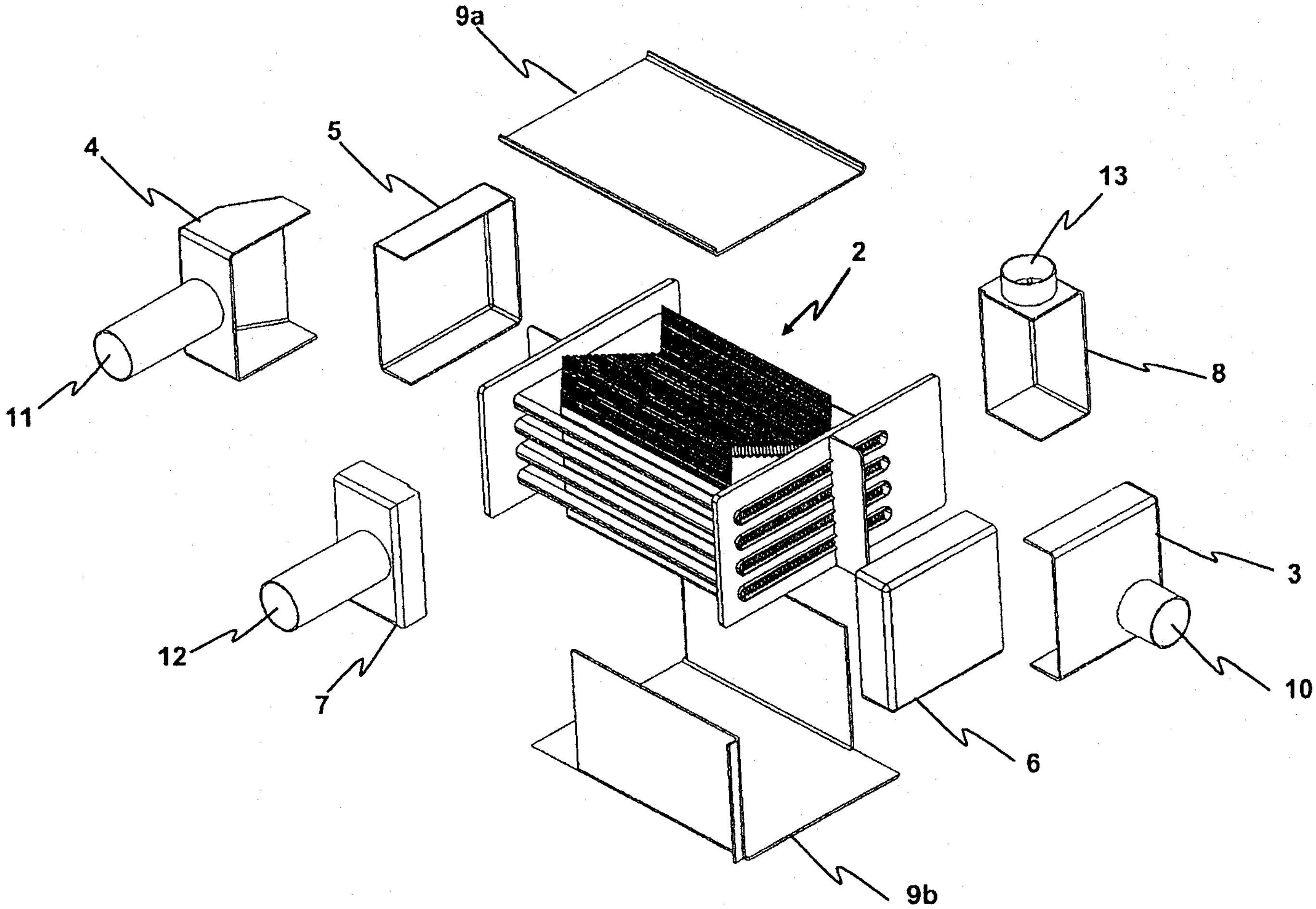


FIG. 4

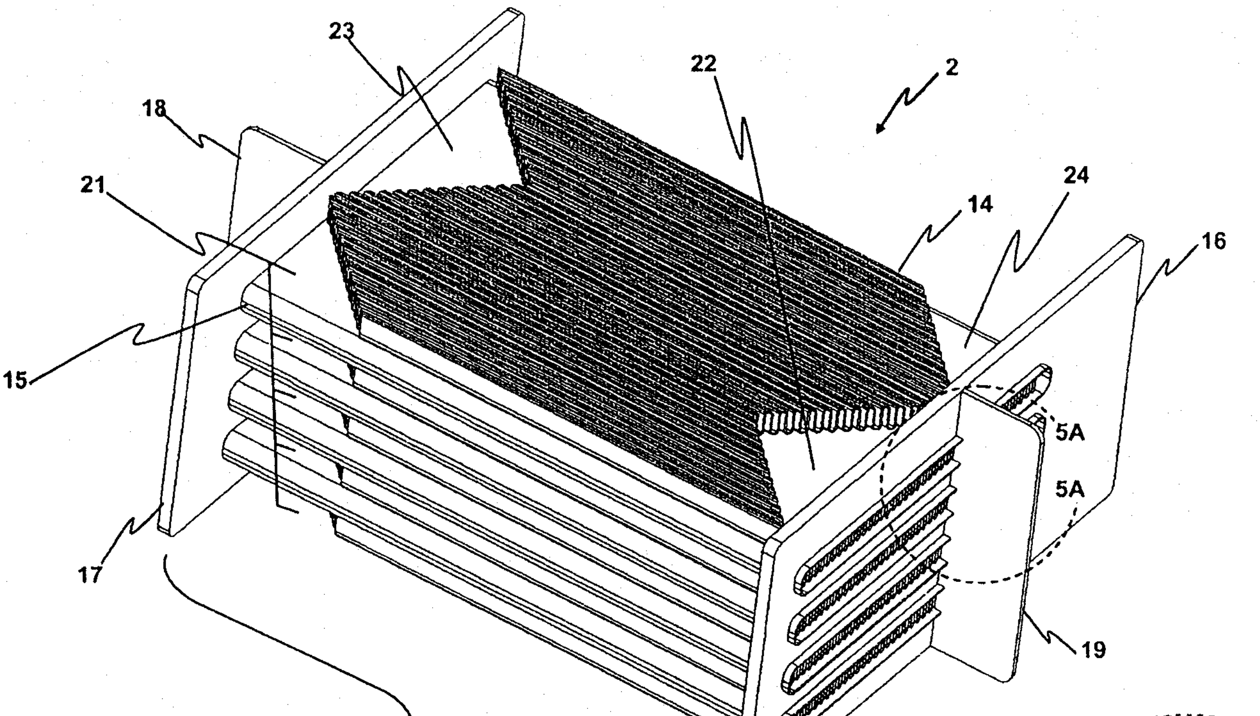


FIG. 5

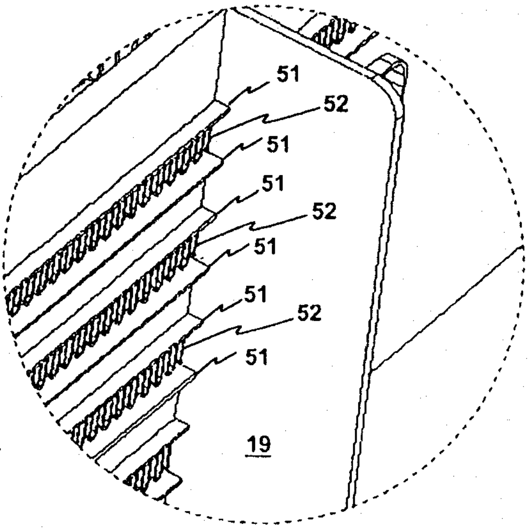


FIG. 5A

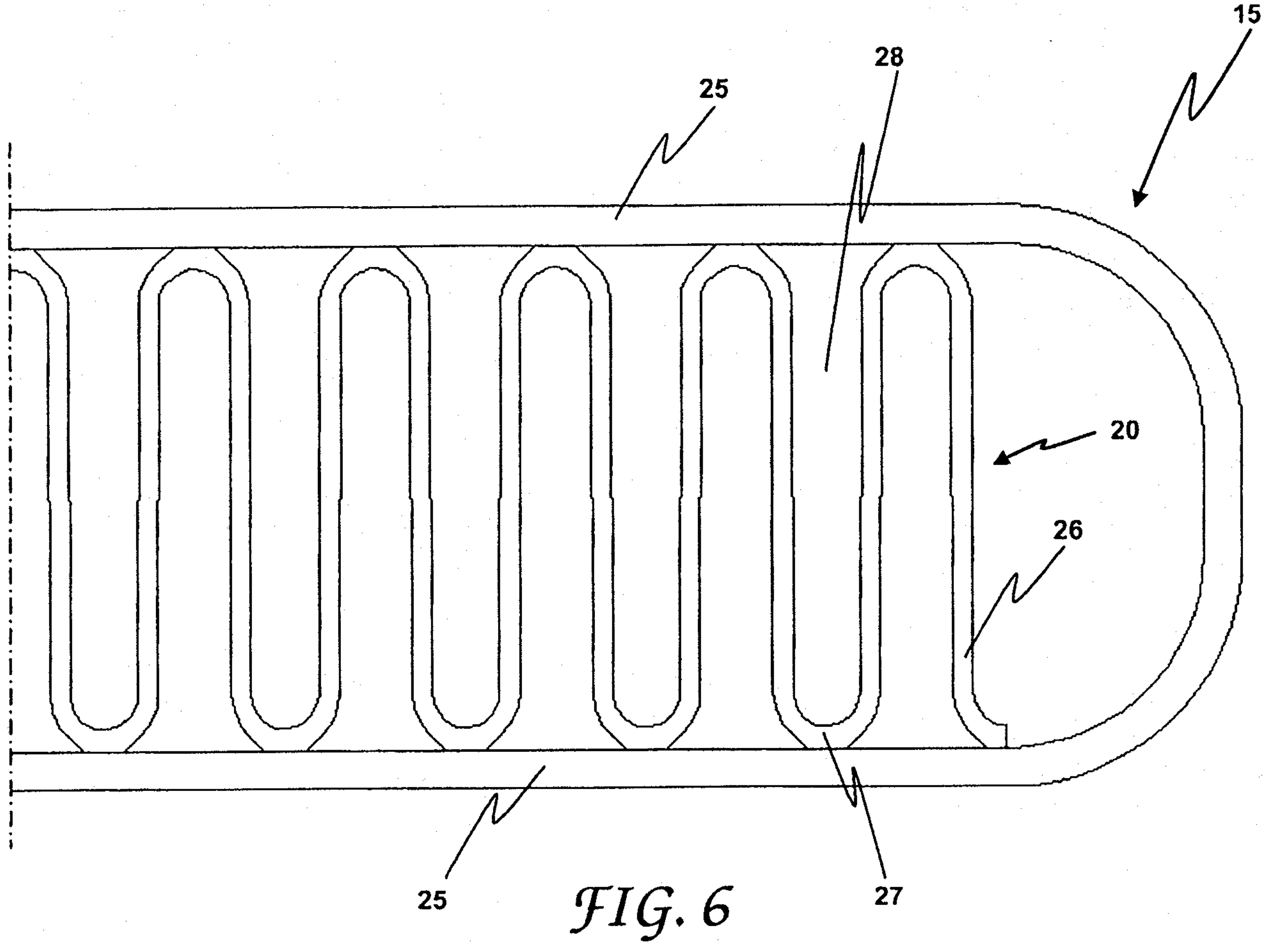


FIG. 6

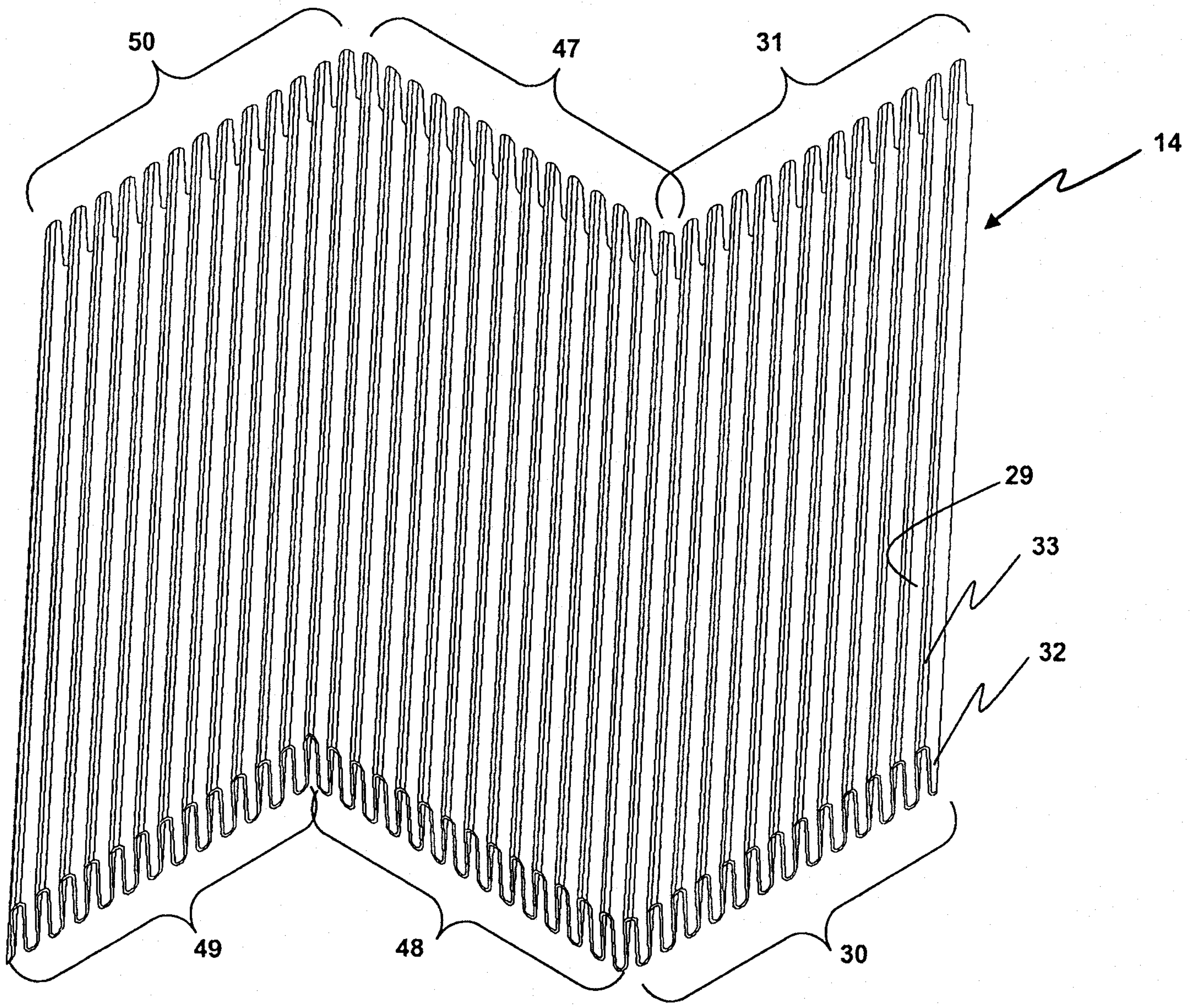


FIG. 7

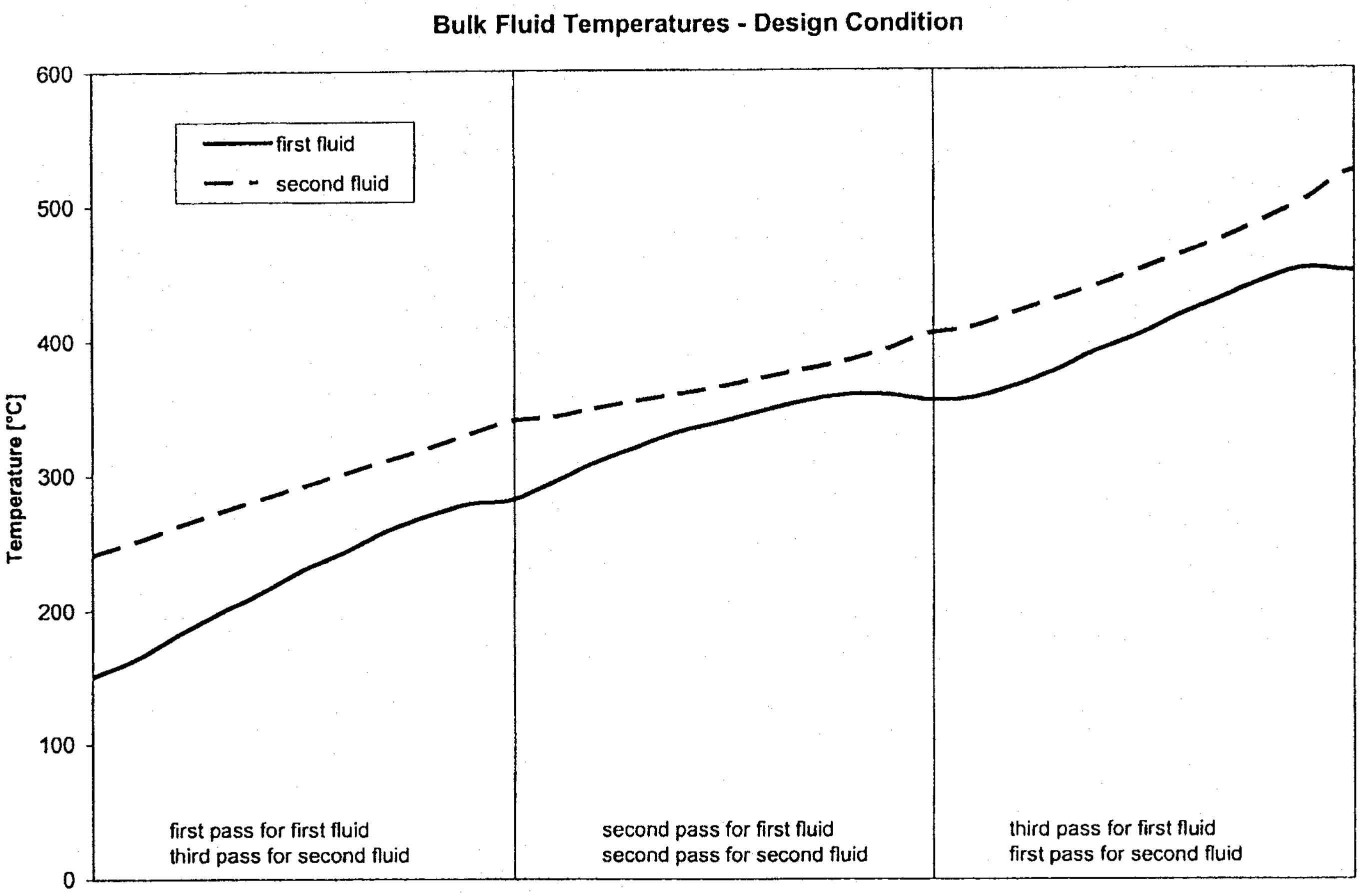
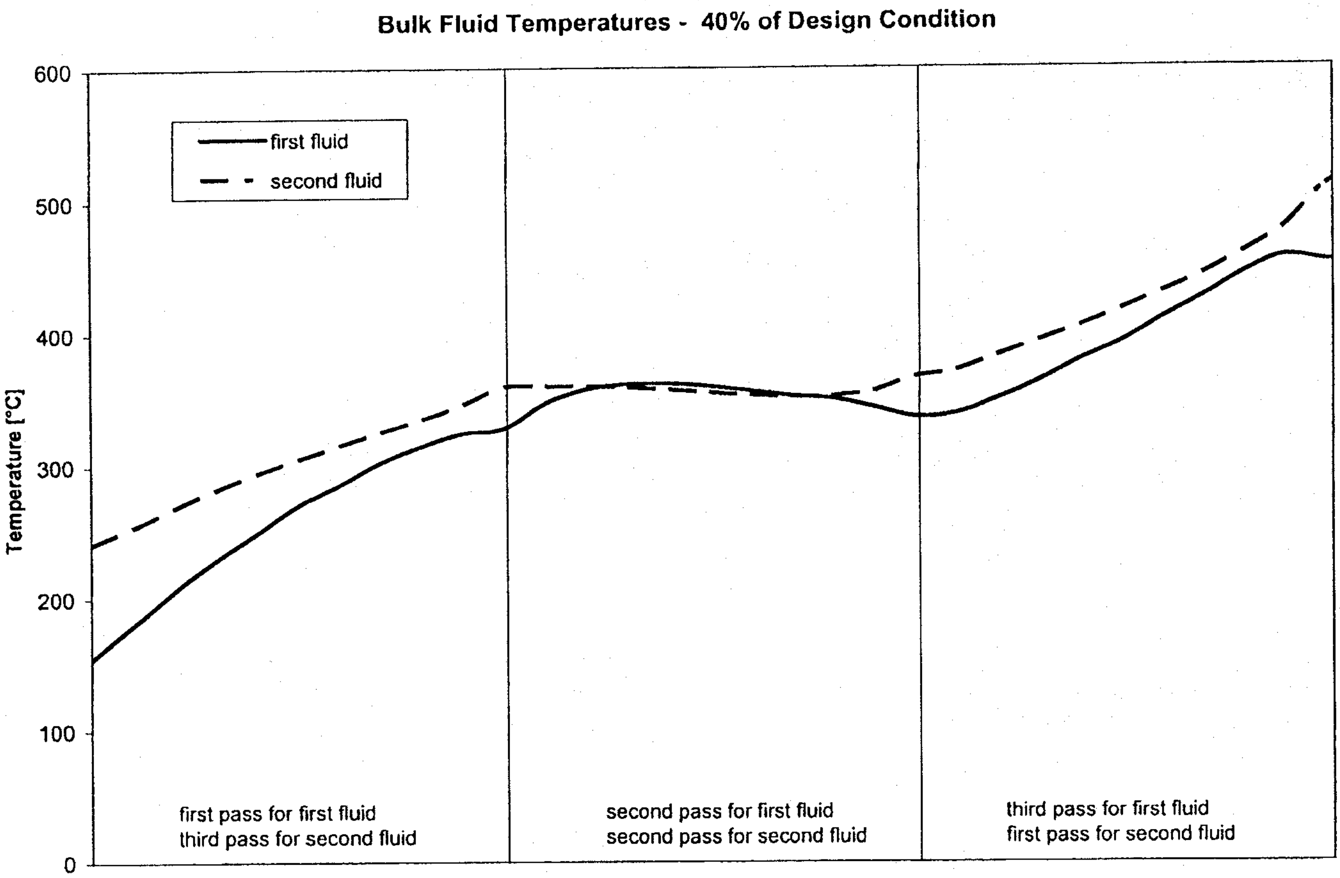

Bulk Fluid Temperatures - Design Condition
Temperature [°C]
600
500
400
300
200
100
0
first fluid
second fluid
first pass for first fluid
third pass for second fluid
second pass for first fluid
second pass for second fluid
third pass for first fluid
first pass for second fluid

FIG. 8


Bulk Fluid Temperatures - 40% of Design Condition
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second fluid
Temperature [°C]
600
500
400
300
200
100
0
first pass for first fluid
third pass for second fluid
second pass for first fluid
second pass for second fluid
third pass for first fluid
first pass for second fluid

FIG. 9

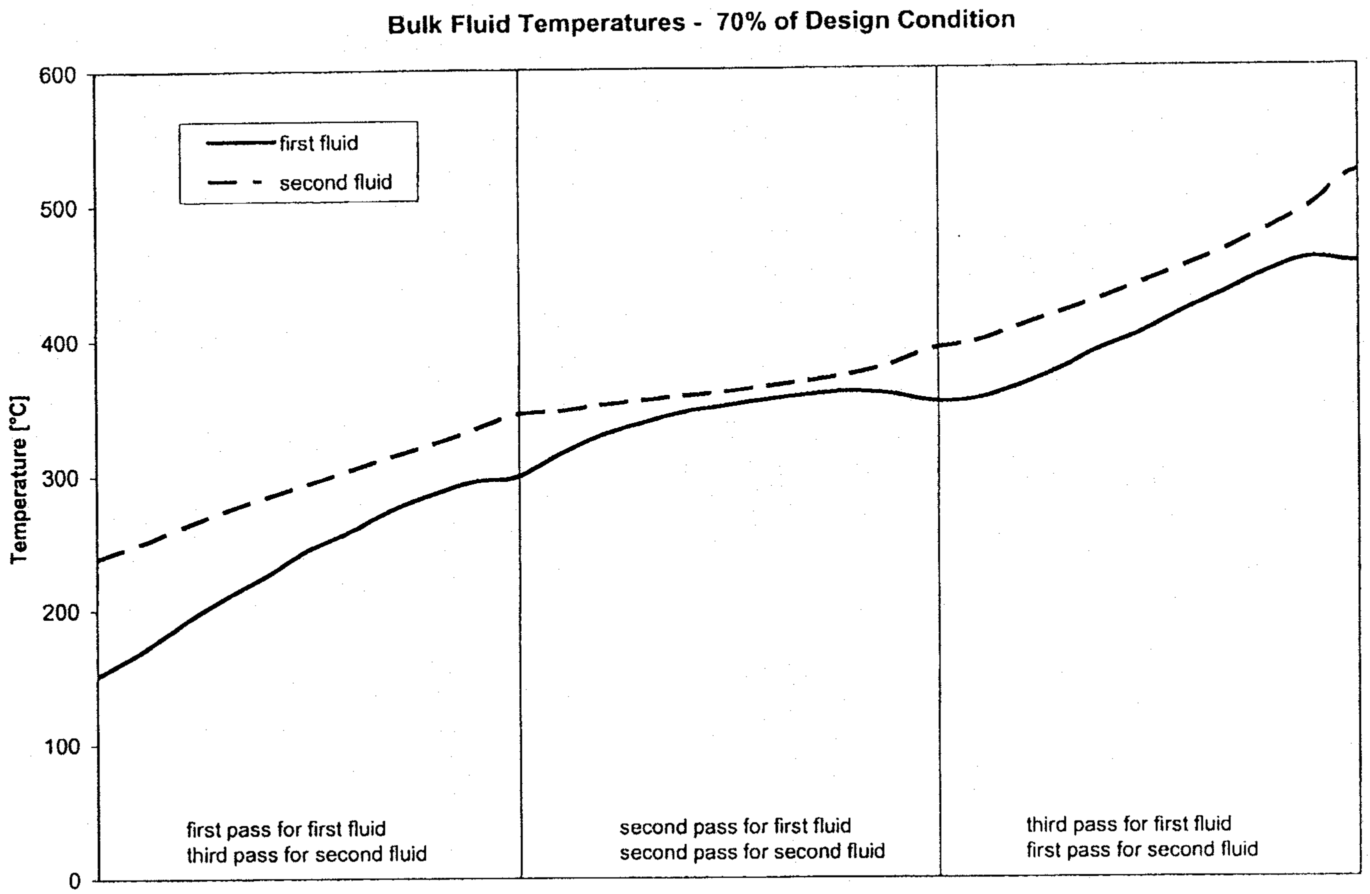
Bulk Fluid Temperatures - 70% of Design Condition
first fluid
second fluid
Temperature [°C]
600
500
400
300
200
100
0
first pass for first fluid
third pass for second fluid
second pass for first fluid
second pass for second fluid
third pass for first fluid
first pass for second fluid

FIG. 10