

Jan. 9, 1951

H. O. McMAHON ET AL

2,537,276

HEAT EXCHANGER

Filed Dec. 22, 1947

6 Sheets-Sheet 1

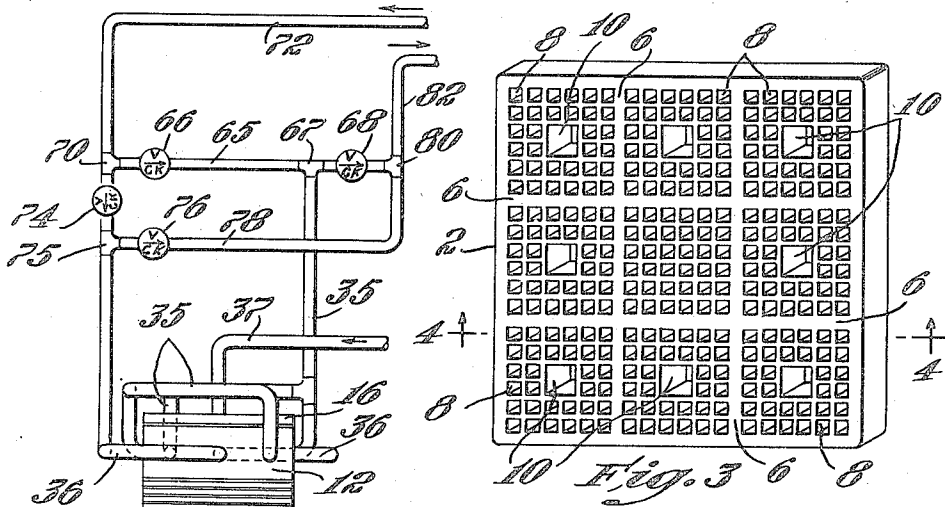


Fig. 1

Fig. 3



Fig. 4

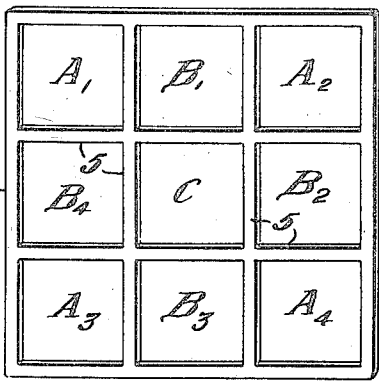
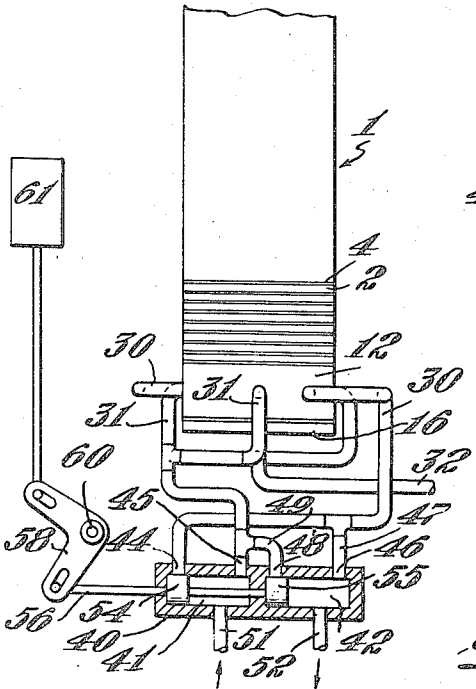


Fig. 5

Inventors
 Howard O. McMahon
 Gustave H. Bleyte Jr.
 Richard B. Finckley
 by Robert Cushman & Crover
 Att'ys.

Jan. 9, 1951

H. O. McMAHON ET AL

2,537,276

HEAT EXCHANGER

Filed Dec. 22, 1947

6 Sheets—Sheet 3

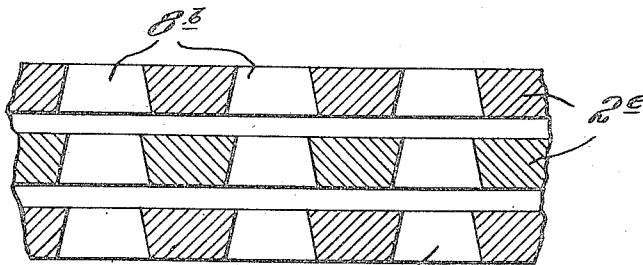
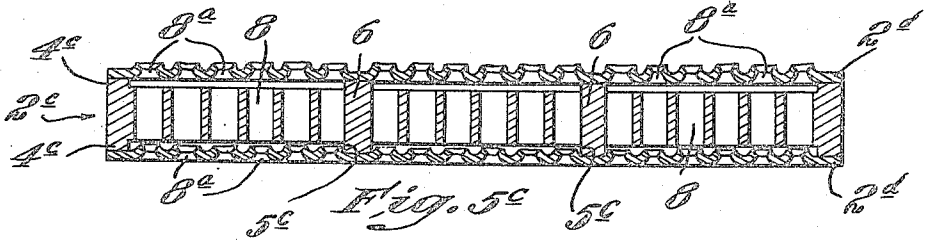
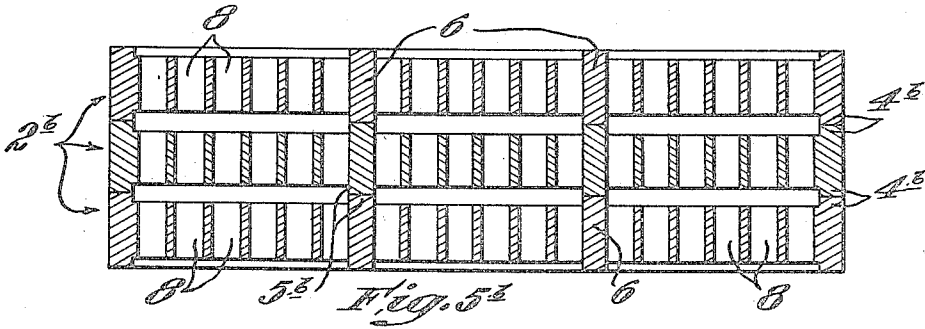
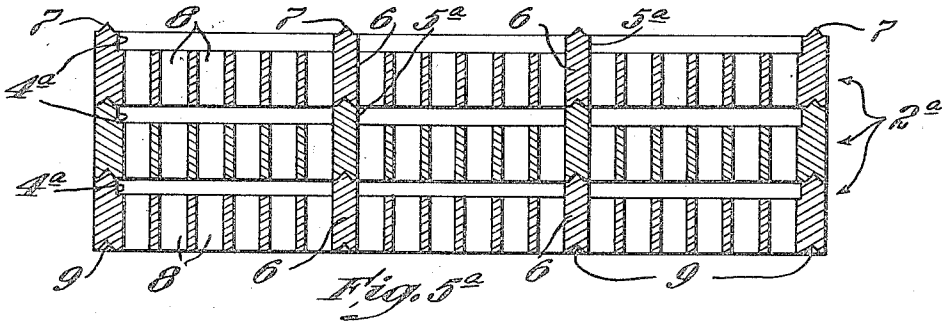


Fig. 6^a 8^a

Inventors
Howard O. McMahon
Gustave A. Bleyle Jr.
Richard B. Hinckley
By Robert Cushman Crow
Att'ys.

Jan. 9, 1951

H. O. McMAHON ET AL

2,537,276

HEAT EXCHANGER

Filed Dec. 22, 1947

6 Sheets-Sheet 4

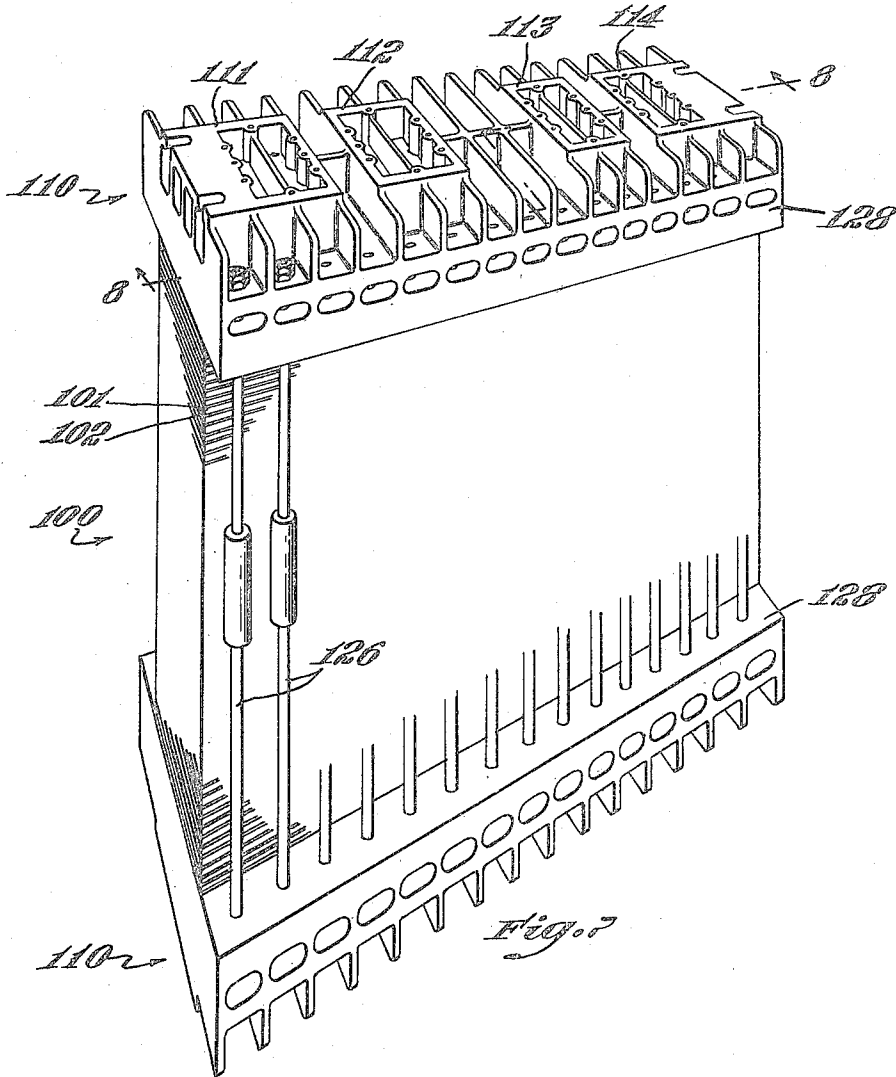


Fig. 7

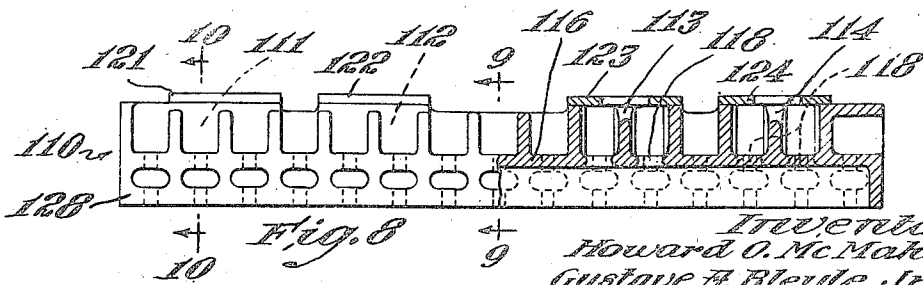


Fig. 8

Inventors
Howard O. McMahon
Gustave A. Bleyer, Jr.
Richard B. Hinchley
by Robert, Cushman & Co.
Att'ys.

Jan. 9, 1951

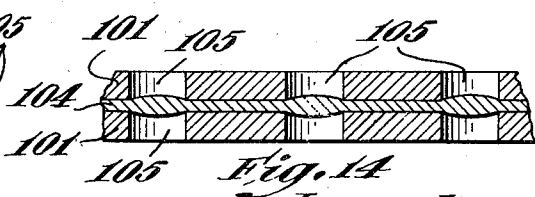
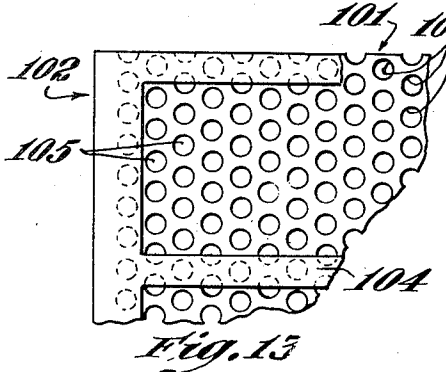
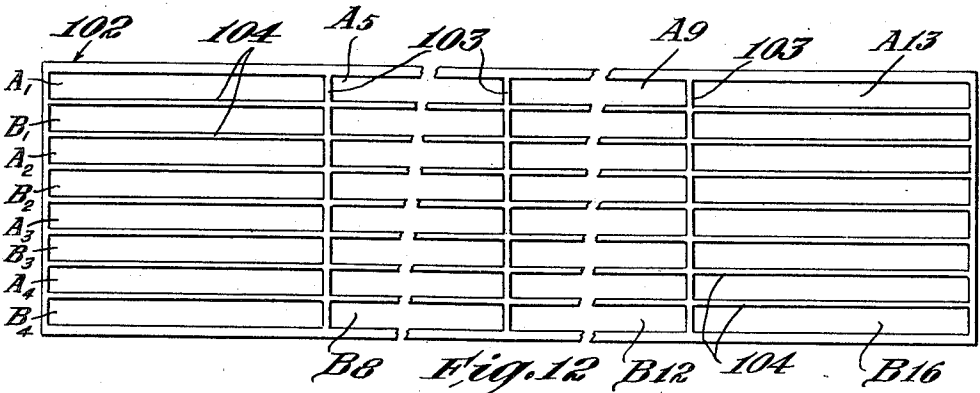
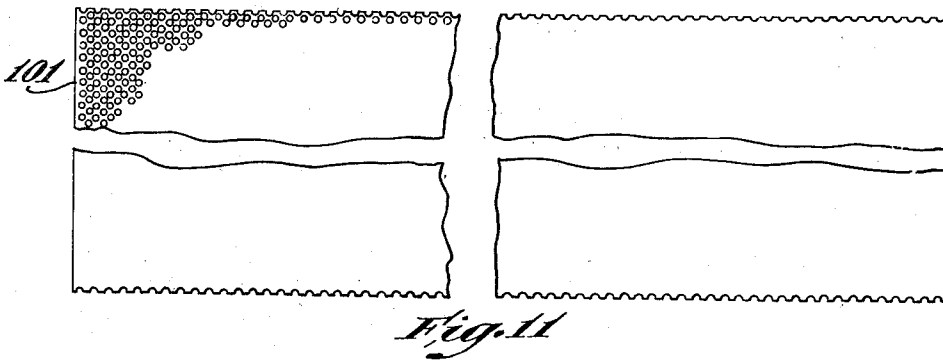
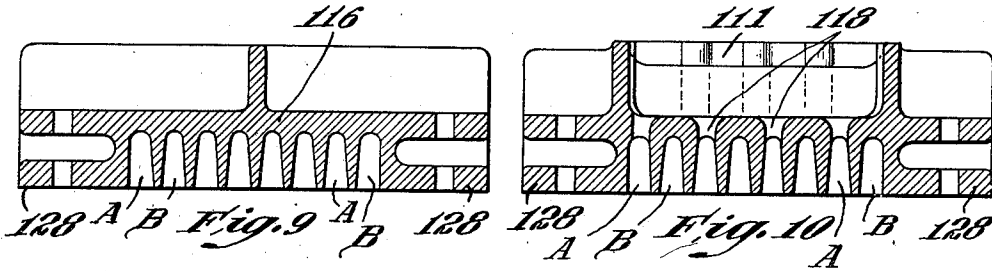
H. O. McMAHON ET AL

2,537,276

HEAT EXCHANGER

Filed Dec. 22, 1947

6 Sheets-Sheet 5



Inventors
 Howard O. McMahon
 Gustave A. Bleyte Jr.
 Richard B. Hinckley
 by Robert Taushman & Coover
 Att'ys.

Jan. 9, 1951

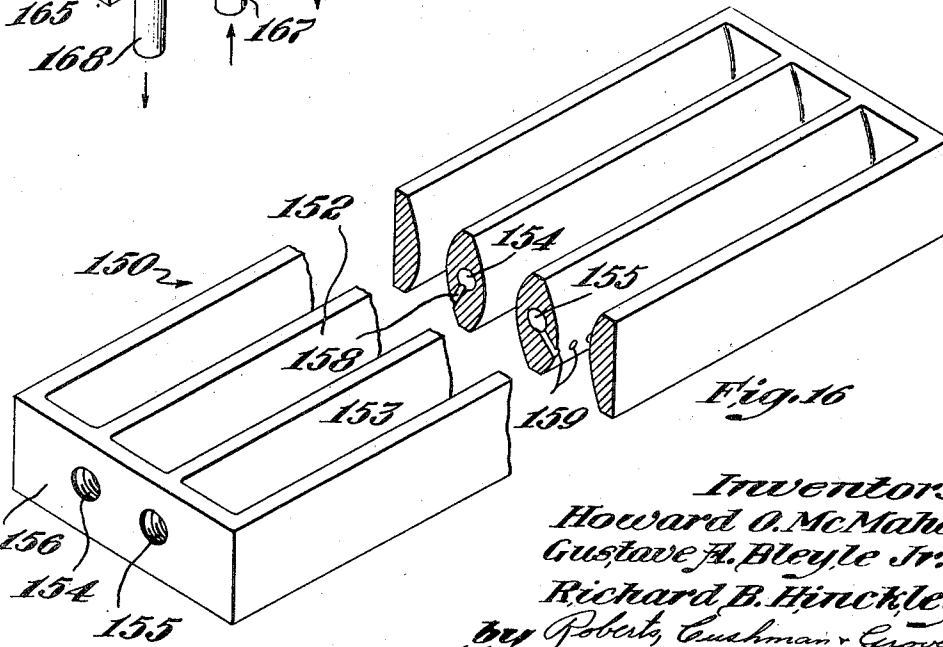
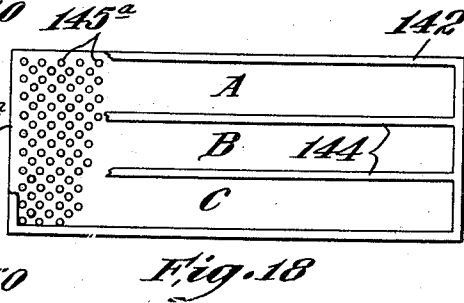
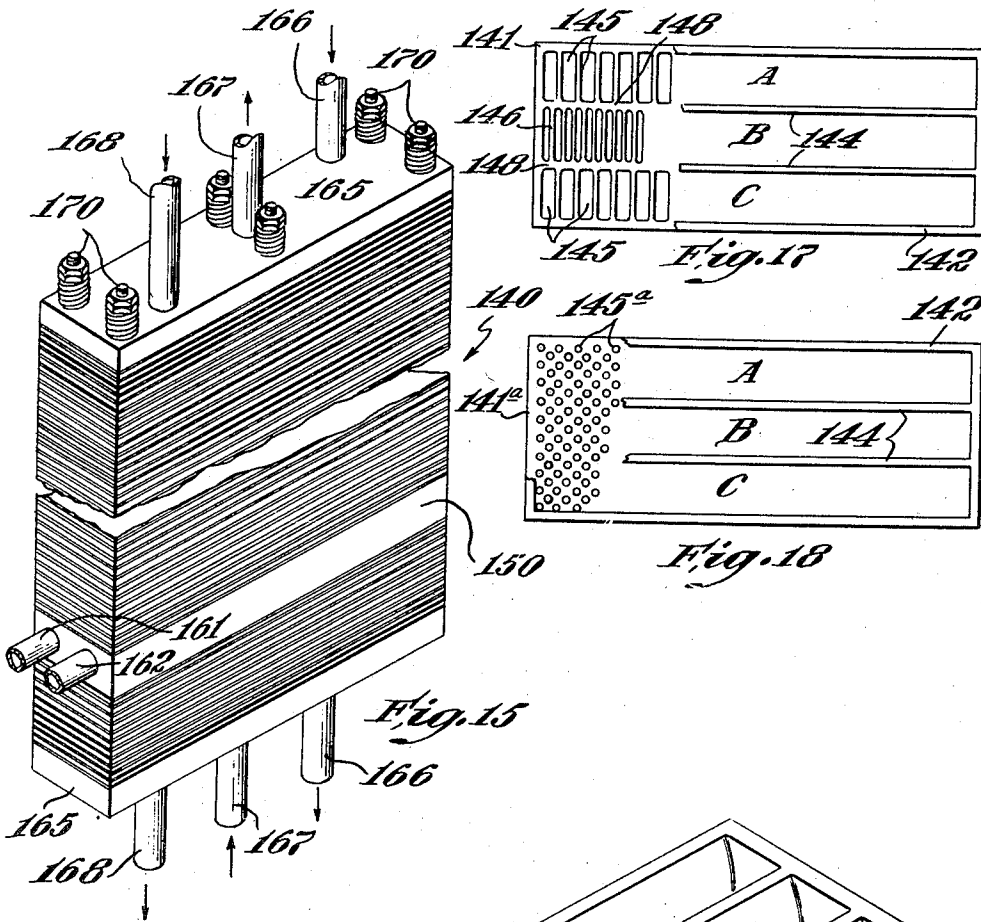
H. O. McMAHON ET AL

2,537,276

HEAT EXCHANGER

Filed Dec. 22, 1947

6 Sheets-Sheet 6



Inventors
Howard O. McMahon
Gustave A. Bleyte Jr.
Richard B. Hinckley
by Robert Cushman & Grover
Att'ys.

UNITED STATES PATENT OFFICE

2,537,276

HEAT EXCHANGER

Howard O. McMahon, Lexington, Gustave A. Bleyle, Jr., Melrose, and Richard B. Hinckley, Dorchester, Mass., assignors to Arthur D. Little, Inc., Cambridge, Mass., a corporation of Massachusetts

Application December 22, 1947, Serial No. 793,186

12 Claims. (Cl. 257-245)

1

This invention relates to an improvement in heat exchangers and the method of effecting an efficient heat exchange between two or more fluids.

Numerous attempts have been made to produce heat exchangers which are efficient and reliable in operation and relatively inexpensive to manufacture, particularly in the application of heat transfer from one gaseous fluid to another, where the heat transfer rate is low and consequently very large surface is required. To this end, heat exchangers embodying various types of laminated constructions have been suggested. The majority of such suggestions have shown various forms of extended surface brazed or soldered between sheets of metal and generally the laminated sheets extend in a direction parallel to the direction of flow. Constructions such as are shown in Wilke, No. 1,863,586 and Schubart, No. 1,734,274, employ laminations perpendicular to the direction of flow of the fluid streams and, although possessing certain advantages, are nevertheless subject to serious objections which limit their utility.

In constructions exemplified in the former patent, which embodies perforated metal plates interposed between gaskets of substantially the identical size and shape, the interior walls of the fluid passages are continuous and the number of square feet of heat transfer surface is objectionably low. The heat transfer coefficient is also low so that the efficiency of the heat exchanger is poor. On the other hand, in constructions exemplified in the latter patent, having screens or wire mesh interposed between the gaskets defining several passageways, the heat transfer coefficient and exposed surfaces are both quite high, but the pressure drop is objectionably high.

Moreover, in such constructions the wire mesh not only acts inefficiently as a heat transfer medium, due to the fact that only half the metal (i. e., the strands running in one direction) is used advantageously, but also presents, due to its reticular structure, the difficult problem of providing a fluid-tight seal about each of the passages, particularly at high pressures. Hence, the advantages of such constructions are, as a practical matter, more than offset by low efficiency, poor performance, manufacture and assembly problems, and also the difficulty of reproducing units having substantially the same performance characteristics.

The principal objects of the present invention are to overcome the aforementioned difficulties and objectionable features and to provide an ef-

2

cient and reliable exchanger designed so that it may be advantageously employed not only in various systems for separating fluid mixtures, but also in gas turbine and the like installations; to provide a heat exchanger particularly suitable for use in reversible flow systems which require identical flow characteristics in each channel or passage and in either direction; to provide a heat exchanger which has a great flexibility of design and construction so that, if desired, the size and length of the fluid passages and the various factors affecting flow characteristics, heat exchange, etc., can be varied or modified to suit any particular requirement; to provide a heat exchanger which can be disassembled for cleaning and repair and readily assembled without the necessity of brazing, welding or soldering parts; and to provide a heat exchanger which can be economically manufactured by mass production methods with the assurance that each unit has substantially identical performance characteristics permitting the substitution or replacement of one unit by another in any system without making compensating adjustments.

A more specific object is to provide an improved method of and apparatus for separating the components of a gaseous mixture, wherein the incoming mixture is subjected to a greater cooling action by the effluent than has heretofore been possible, thereby increasing the over-all efficiency of the system.

Further objects relate to various features of construction and will be apparent from the consideration of the following description and the accompanying drawings, wherein:

Fig. 1 is a schematic view of a part of a system for producing oxygen from compressed air, which embodies a heat exchanger constructed in accordance with the present invention;

Fig. 2 is an isometric exploded view illustrating the various parts of the heat exchanger shown in Fig. 1;

Fig. 3 is an enlarged isometric view of one of the foraminous plates of the heat exchanger;

Fig. 4 is a section on the line 4-4 of Fig. 3;

Fig. 5 is an enlarged isometric view of one of the fenestrate separators of the heat exchanger;

Fig. 5a is a fragmentary vertical section through an assemblage of foraminous plates formed on one face with integral separators of full thickness;

Fig. 5b is a view similar to Fig. 5a, but showing foraminous plates formed on both faces with integral separators of half thickness;

Fig. 5c is a view similar to Fig. 5a, but showing

a foraminous plate formed on both faces with an integral separator of full thickness, the plate alternating with plates having pierced openings;

Fig. 6 is an enlarged section through a group of the assembled plates of the heat exchanger, illustrating the flow characteristics through and about the openings in the plates;

Fig. 6a is a view similar to Fig. 6 but showing foraminous plates formed with tapered openings;

Fig. 7 is a perspective view illustrating a modified form of heat exchanger;

Fig. 8 is a longitudinal section through the header approximately on the line 8-8 of Fig. 7;

Figs. 9 and 10 are transverse sections through the header on the lines 9-9 and 10-10, respectively, of Fig. 8;

Fig. 11 is a top plan view of one of the foraminous plates;

Fig. 12 is an enlarged plan view of one of the fenestrate separators;

Fig. 13 is an enlarged detail of the foraminous plate and associated separator shown in Figs. 11 and 12;

Fig. 14 is an enlarged section through the plate and associated separator shown in Fig. 13;

Fig. 15 is an isometric view of another form of heat exchanger;

Fig. 16 is an enlarged isometric view of the injector embodied in the heat exchanger of Fig. 15;

Figs. 17 and 18 are plan views of different forms of foraminous plates and associated separators; and

Fig. 19 is a schematic view of a gas turbine system embodying a heat exchanger constructed in accordance with the present invention.

A heat exchanger constructed in accordance with the present invention comprises a plurality of substantially identical flat foraminous plates of relatively high thermal conductivity, and fenestrate or frame-like separators alternating with the foraminous plates and formed with one or more ligaments extending between opposite edge portions of the separators. The plates may be of cast iron, steel, copper, aluminum or the like suitable metallic material, although for certain uses non-metallic compositions, such as a petroleum coke base carbon rendered impervious by impregnation with a synthetic resin (Karbate), may advantageously be used.

The separators may be of any suitable material, metallic or nonmetallic, which preferably is at least partially deformable and hence any of the well-known fibrous or nonfibrous gasket materials may be used, including such soft metals as lead and lead alloys, etc., the particular selection of both the material for the separators and the foraminous plates depending upon the temperatures to which these elements are to be subjected and the character of the fluids to be treated.

Should there be any hazard due to the use of combustible material, as when oxygen is one of the fluids, it may be necessary to use for the separators an inert or noncombustible material, such as an asbestos composition, a polytetrafluoro-ethylene (Teflon) resin, a silicone resin, or a glass fiber or mineral wool base impregnated with a noncombustible binder such as a silicone resin, all of which materials are particularly suitable since they are relatively deformable.

Although separators having some degree of deformability are preferred in order to insure a gas-tight seal about the fluid passages, it is to be understood that, if desired, separators of relatively hard or nondeformable material, such as

steel, etc., may be used in conjunction with foraminous plates of a relatively deformable material such as aluminum. In any event, as long as one of these elements is relatively soft or compressible, as compared with the other, there will be sufficient deformation of one of the contacting surfaces to insure a gas-tight seal.

An alternative arrangement is to make each plate integral with one of its adjacent separators. This may be done, for example, by forging a plate which on one side has integral ridges corresponding in configuration to those of the individual fenestrate separator herein described. A sufficient number of these plates are then laid together to form a heat exchanger of the desired capacity. In such an arrangement it is necessary that the material of the plates and their integral separators be sufficiently deformable so that a tight seal is attainable when they are clamped together; otherwise very accurate machining (which, though possible, is rarely practical) is required to insure absolutely plane parallel surfaces and hence a tight seal.

As another modification of this construction, each plate may be made similarly but with an integral separator on each face, each such separator having for example one half of the thickness of the individual fenestrate separator which would otherwise be used.

As still another modification, such plates may be made with integral separators on each side, having the full thickness of the individual separators, and these plates may then be laid up alternating with plain plates (i. e., plates without integral separators). If one component is made of a sufficiently deformable material, and the other of a sufficiently deformable or of a nondeformable material, as already described in connection with the separate plates and separators, a gas-tight seal is attained on clamping the structure together.

In any of these constructions employing integral separators, the faces of the separator ridges may be flat, or they may be grooved or ridged or otherwise shaped and corresponding grooves or recesses are then provided in the opposite face of each plate into which the contours of the separator ridges fit closely. While a degree of deformability is still required in these integral plate-separator structures, the grooves, ridges or the like serve in particular to prevent any sideways slippage or movement of any of the plates.

The flatness of the plates, in any event, may be more or less relative, thus permitting plates having areas which are more or less cupped or dished, for increasing the surface contact area. In all cases, however, those portions of any one face of any plate which are in contact with the corresponding separator (or plate, if the separators are integral with the plate as above described) are flat and in the same plane. Likewise, when punching or piercing the openings in the foraminous plates, it is possible to leave the metal which occupied the holes still attached to the plate, in the form of tubular projections, or louvre-like fins, or other shapes depending on the nature of the punching operation. Such resulting configurations are permissible in the plates of the present invention in instances where such projections or fins do not occur in those areas of the plates which are in contact with the separators to such an extent that proper sealing of the passages is prevented.

The plates and separators are so assembled that the openings in the plates are in substantial

5

6

alignment and the ligaments of the separators are likewise aligned so as to surround or enclose the same number of openings in the plates, the ligaments thus defining a plurality of regularly interrupted fluid passages, the size and shape of each being determined by the arrangement of the ligaments. Thus, by varying the size, shape and arrangement of the ligaments of the separators, a plurality of fluid passages having the same or different flow characteristics, capacities, etc., may readily be provided without changing the design of the foraminous plates. With this construction and arrangement the openings in each of the plates are in heat-exchange relation with each other through the material of the plate, and the separators not only maintain the plates in predetermined spaced relation but, due to their deformable character, also provide fluid-tight seals about each of the passages.

If the openings in the plates are not in substantial alignment, the pressure drop through the apparatus is increased and becomes excessive if the openings are greatly out of line. A slight degree of deviation from perfect alignment will frequently occur; and slight deviation is permissible as long as it does not have any significant effect upon the pressure drop through the heat exchanger. Expressed otherwise, the alignment should be such that substantially the lowest possible pressure drop is attained with the particular configurations of plates used in a given apparatus.

The opposite ends of the exchanger are provided with headers or manifolds through which the fluids are admitted to and discharged from the heat exchange passages, and any suitable means may be provided for clamping or otherwise holding the parts in fixed position. Where the temperature differential is substantial, spring-loaded tie rods extending lengthwise of the fluid passages are recommended since they permit both expansion and contraction without impairing the fluid-tight seals.

Since tie rods increase considerably the weight of the heat exchanger assembly, it may be advantageous in some instances to omit them, and to make up instead a unitary structure of metal plates and separators brazed together. This can be done, for example, by assembling together foraminous plates of copper, and separators of iron, and passing the assembly through a brazing furnace in an atmosphere of hydrogen, thereby forming a bonded structure requiring no tie rods. Such a structure not only eliminates the use and the weight of the tie rods, but it is also free of any tendency toward sideways slippage of the plates and separators. On the other hand, it involves a relatively expensive brazing step, and the resulting structure cannot be practically disassembled for cleaning or repair, so for most uses the herein described assembly using tie rods is preferred.

The openings in the foraminous plate may be of different size, shape and arrangement, depending upon the desired heat transfer coefficient and performance characteristics (see Norris and Spofford, Transactions A. S. M. E. 64, 489). In most cases it is preferable to provide plates having a thickness less than the minimum dimensions of the openings therein and separators having a thickness less than that of the contiguous plates, thereby providing interrupted fluid passages which induce a high heat transfer coefficient between the fluid and the plate without causing an objectionable resistance to flow. It is also im-

portant that the combined area of the openings in the foraminous plate have a suitable relation to the area about the openings, thereby to insure a good heat transfer from one section of the plate to and from all other sections consistent with the flow characteristics and thermal properties of the fluids. Thus, in the case of gaseous fluids at reasonably low pressure (e. g., 100 p. s. i. or less) the combined area of the openings may preferably be approximately equal to the area about the openings; whereas for most liquids the percentage of open area may be considerably less than 50%; and for rarefied gases the optimum percentage of openings may be considerably greater than 50%. If desired, the percentage of open area in one fluid passage may differ from that of another, depending upon the particular fluid to be handled. The optimum percentage of open area is also dependent upon the widths or cross-sectional shape of the fluid passages, because of the fact that heat must be transferred from one passage to another, and the greater the length of the heat path the more metal is required to transmit heat in order to provide a proper delta T.

Where it is desired to provide a heat exchanger having fluid channels or passages which may be varied, the foraminous plates are formed with regularly spaced openings and the separators are provided with ligaments having a width which is greater than the center-to-center distance between the openings and greater than the major dimension of the openings. With this construction the ligaments may be so arranged as to inclose any desired number (within practical limits) of openings in the plates, thereby providing fluid passages of the desired size and shape without requiring specially designed plates.

The openings in the plates may, if desired, have more or less tapered sides, thus providing essentially a number of rows of little nozzles in series throughout the length of the exchanger or any desired part thereof. When the plates are made by forging or die-casting, there is necessarily at least a very small taper of the sides of the openings, and this taper can advantageously be appreciable when forging or die-casting. The taper results in greater turbulence in the fluid flow, and hence in more effective heat transfer. On the other hand, it increases the pressure drop. Hence the amount of taper, if tapering is employed, should be such as will accomplish a proper and practical balance between heat transfer and pressure drop.

Another aspect of the invention relates to the separation of the components of fluid mixtures, and more particularly to the separation of oxygen from compressed air. In virtually all such systems it is the practice to pass the incoming compressed air into heat-exchange relation with the separated oxygen and/or nitrogen which are at relatively low temperatures. Where such heat exchange is conducted in a system embodying a heat exchanger constructed in accordance with the present invention, there may be provided between two of the foraminous plates adjacent to the warm end of the exchanger, an injector for atomizing or otherwise injecting water into one or more of the effluent passages, preferably the passages through which the nitrogen is flowing. The relatively dry effluent gas and heat absorbed from the incoming gas or air are effective to vaporize the injected water and due to the high latent heat of vaporization of water, there is obtained a greatly increased cooling action which enhances the over-all efficiency of the system.

A further advantage of a heat exchanger embodying a water injector is that it provides a novel method for unbalancing a reversing heat exchanger such as is shown in the copending application of Samuel C. Collins, Serial No. 661,253, filed April 11, 1946, in which the unbalancing takes place at the cold end, through the conduction of the cooled compressed gas through a passageway in heat-exchange relation with the cold end of the exchanger; whereas in a heat exchanger embodying the hereindescribed water injector, the unbalancing takes place at the warm end of the exchanger in a very simple, efficient and inexpensive manner.

Moreover, in practically all systems for separating oxygen from compressed air, as well as other processes using compressed gases which are conducted through a heat exchanger, the herein described water-injection arrangement may be advantageously employed as a substitute for the expensive and cumbersome after-coolers which are conventionally used for cooling the compressed gases before they enter the heat exchanger.

Another aspect of the invention relates to gas turbines and the like systems wherein it is desired to transfer as much of the heat as is practical from the exhaust combustion gases to the compressed air. A heat exchanger constructed in accordance with the present invention may advantageously be used in all such installations due to the relatively low pressure drop, high efficiency and low space requirements, as compared to heat exchangers heretofore used.

A particularly advantageous feature of a heat exchanger constructed in accordance with the present invention is that any given design may be readily reproduced with substantially identical performance characteristics, thus permitting the replacement of one unit by another without the necessity of making compensating adjustments. The same structural features likewise insure the provision of substantially identical flow passages within the same heat exchanger so that it can be used in systems where the fluid flow is periodically reversed, such as is shown in the aforesaid copending application of Samuel C. Collins.

Referring to the embodiment of Figs. 1 to 6, which shows what is now considered to be one of the preferred forms of heat exchangers which may be advantageously used in the above mentioned Collins system for separating oxygen from air, the numeral 1 designates the heat exchanger which comprises a plurality of substantially identical foraminous plates 2 interposed between separators 4 formed with ligaments 5. Since this particular application requires passages for the incoming air and outgoing nitrogen and oxygen, the design of the plates and separators is such as to provide nine separate fluid passages, as indicated in Fig. 2, the eight outer passages A1, A2, B1, B2, etc., being for the air and nitrogen, and the inner passages C being for the oxygen.

Each of the plates 2 preferably consists of a die casting of copper, aluminum or other suitable material of good thermal conductivity, formed with partitions or webs 6 corresponding to the ligaments 5 of the separators, although as hereinafter shown, such plates may be of punched sheet stock. The webs 6 cooperate with the ligaments 5 to define the nine fluid passages for the air, nitrogen and oxygen and, as above indicated, the separators are preferably of compressible, noncombustible material such as a polytetrafluoro-ethylene (Teflon), a silicone resin,

asbestor, or a glass fibre or mineral wool base impregnated with a silicone resin. Between the webs 6, each plate is formed with a plurality of small, square-shaped openings 8 and a larger central opening 10. As indicated in Figs. 3 to 6, the thickness of each plate may be of the order of two to three times that of the separators, thereby providing sufficient metal to insure a good heat transfer from one section of each plate to another.

The plates and separators are assembled so that the ligaments are coextensive with the outer faces of the webs 6 and thus not only insure proper spacing of the plates, but also gas-tight seals about each of the nine passages. When thus assembled, the openings 8 and 10 are in substantially precise alignment and it will be noted, as illustrated in Fig. 6, that the openings 8 define a plurality of regularly interrupted channels in each fluid passage and that the channels are interconnected so as to expose the maximum heat transfer surface of the plates. A further feature of this construction is that the channels defined by the openings 8, being regularly interrupted, induce a high heat transfer coefficient between the fluid and the plates without causing an objectionable resistance to flow. Moreover, the fluid passages are substantially identical to each other and hence necessarily have the same performance characteristics. Accordingly, the fluid flow through the different groups of passages may be reversed, as hereinafter explained, without affecting the balanced operation of the system.

The plates and separators may, as above noted, be formed integral with each other as illustrated in Figs. 5a to 5c and a sufficient number of such plates are assembled to form a heat exchanger of the desired capacity. In Fig. 5a the plates 2^a are formed on one face with integral separators 4^a and their ligaments 5^a of full thickness, i. e., a thickness substantially the same as that of the corresponding parts of the separator 4 and, if desired, the upper faces of the separators 4^a including the ligaments 5^a may be formed with ridges or projections 7 and the corresponding parts of the undersurface of the plates may be formed with grooves or recesses 9 to receive the projections 7 of the contiguous separator, thereby providing an interlocking seal which prevents lateral slippage of the assemblage. In all other material particulars each of the plates 2^a may be substantially identical to the plate 2.

In Fig. 5b the plates 2^b are formed on each face with integral separators 4^b and their ligaments 5^b of half thickness, i. e., a thickness about one-half that of the corresponding parts of the separator 4. In Fig. 5c the plate 2^c is formed on each face with integral separators 4^c and their ligaments 5^c of full thickness and such plates alternate with the plates 2^a which may be of sheet metal or the like suitable material pierced to form tubular projections defining the opening 8^a, it being understood that, if desired, any other type of foraminous plate may be used in place of the plate 2^a.

Although the openings in the plates herein described may be formed with little or no taper, as indicated in Figs. 4 and 6, if desired such openings may be of frustoconical shape or otherwise tapered, as indicated at 8^a in Fig. 5c and at 8^b in Fig. 6a, in which case there is produced a greater turbulence in the fluid flow and hence a more effective heat transfer, although the pressure drop is increased as already pointed out.

9

The number and size of plates to be used in the heat exchanger will depend on the desired capacity and having determined, empirically or otherwise, the heat exchange performance of a given number of plates and associated separators, a heat exchanger of greater or lesser capacity may be made by using more or less plates, as the case may be. For example, in the system illustrated in Fig. 1 the heat exchanger is designed to handle approximately 22 standard cubic feet of incoming air or gas per minute and approximately an equal amount of outgoing gases with a pressure drop through the exchanger of about 1.25 p. s. i. The inlet and outlet temperatures of the gases at the warm end of the exchanger are about 80° F. and 70° F., respectively, and the inlet and outlet temperatures at the cold end are about -250° F. and -212° F., respectively. Accordingly, the plates may be approximately 3½" square (over-all dimension) and about 0.12" thickness and a stack of 335 of such plates with interposed separators will provide a sufficient number of heat-exchanger elements to handle the above requirements.

Regardless of the number or type of plates employed, each of the opposite ends of the stack is provided with a header or manifold 12 having partitions 14 corresponding to the ligaments 5 and webs 6, and a closure member 16, as shown in Fig. 2. The side walls of each header are provided with openings 18 each communicating with one of the outer fluid passages, and each closure member is provided with a central opening 20 communicating with the inner passage of the header, and eight small openings corresponding to and aligned with the openings 10 of the plates 2, which openings, as shown in Fig. 2, are centrally disposed with respect to the passages defined by the ligaments 5.

The plates 2, headers 12, closure members 16 and interposed separators 4 are firmly clamped together by eight tie rods 22 which extend through the stack from one header to the other, as illustrated in Fig. 2. The opposite ends of the tie rods are threaded and carry clamping elements such as acorn nuts 24 and, if desired, short lengths of coiled compression springs 25 may be interposed between the nuts 24 at one end and the adjacent closure members to permit expansion and contraction of the stack without impairing the sealing action of the separators.

In order to connect the heat exchanger into the system shown in Fig. 1, the openings 18 of the headers 12 at one end are connected with manifold lines 30 and 31, the line 30 and associated branches interconnecting the passages A₁ to A₄ and the line 31 and associated branches interconnecting the passage B₁ to B₄, and a single line 32 is connected to the opening 20 of the adjacent closure member to provide a connection with the central passage C. Likewise, the openings 18 of the header at the opposite end of the exchanger are connected with manifold lines 35 and 36 and a line 37 connects the opening 20 of the closure member at the opposite end. Thus, the lines 31 and 36 provide a communication with the passages B₁ to B₄, the lines 30 and 35 provide a communication with the passages A₁ to A₄, and the lines 32 and 37 provide a communication with the central passage C.

Since the operation of the system requires a periodic reversal or interchange of flow between the fluid in the passages A₁ to A₄ and that in the passages B₁ to B₄, the lines 30 and 31 are connected to a reversing valve mechanism compris-

10

ing a casing 40 having two chambers 41 and 42 separated by a medial partition. The chamber 41 has an outlet 44 connected to the line 30 and another outlet 45 connected to the line 31. The chamber 42 has an outlet 46 connected to the line 30 by a branch 47 and another outlet 48 connected to the line 31 by a branch 49. Inlet lines 51 and 52 are respectively connected with the chambers 41 and 42, the inlet line 51 being connected with a suitable source of compressed air and the line 52 either being connected with a receiver for nitrogen, or being vented to the atmosphere. Within the chambers 41 and 42 are piston valves 54 and 55 secured to a common piston rod 56, the outer end of which is connected to a bell crank 58 pivotally mounted at 60. The bell crank 58 is periodically operated by a motor 61, as explained in more detail in the aforementioned Collins application, to shift the valves back and forth from one position to another.

With this construction and arrangement compressed air admitted through the inlet line 51 passes through the chamber 41 and with the valves set as shown in Fig. 1 the compressed air passes from the chamber 41 through outlet 45 into the line 31 and its associated branches leading to the channels B₁ to B₄ of the exchanger. Simultaneously, gaseous nitrogen flowing in the opposite direction through the passages A₁ to A₄ is discharged into the branches associated with line 30, then into the branch 47, chamber 42 and through the outlet 52.

The opposite end of the exchanger may be connected either to the same type of valve mechanism, or to the check valve arrangement herein shown, which is automatically operative to alter the flow through the heat exchanger in accordance with the position of the valves 54 and 55. The check valve arrangement comprises a line 65 connected at one end with the outlet of a check valve 66 and at its other end to a T 67, one branch of which is connected to the line 35 and the other branch with the inlet of a check valve 68. The inlet of check valve 66 is connected with a T 70, one branch of which is connected with the nitrogen line 72 (leading from the processing apparatus) and the other branch with the inlet end of a third check valve 74. The outlet of check valve 74 is connected with a T 75, one branch of which is connected to the line 36 and the other branch to the inlet of a fourth check valve 76, the outlet of which is connected to a line 78. The outlet of the check valve 68 is connected to a T 80, one branch of which is connected to the compressed air line 82 (leading to the processing apparatus) and the other branch is connected with the line 78.

With this arrangement and with the valve mechanism set as shown in Fig. 1, the compressed air admitted through inlet 51 is conducted through the line 31 and associated branches into the passages B₁ to B₄, then through the line 36 and associated branches to the T 75. Check valve 74 opposes flow into the line 72, but the check valve 76 permits flow of air through the line 78, T 80 into the line 82. At the same time nitrogen flowing toward the exchanger in line 72 at a lower pressure than the air in line 82 passes through the T 70, then through check valve 66, line 65, T 67 into line 35, it being understood that the greater air pressure in the lines 36 and 78 is effective to hold the check valves 68 and 74 closed so that the flow of nitrogen is confined to the line 65 and 35. The line 35 and associated branches conduct the nitrogen into the passages

A₁ to A₄ from which it is discharged into the line 30 and associated branches, then through the branch 47, chamber 42 and outlet 52.

When the motor 61 shifts the valves 54 and 55 to the opposite ends of the chambers 41 and 42 (in which position the valves close the ports 45 and 46 and open the ports 44 and 48), the incoming compressed air passes through the line 30 and associated branches into the passages A₁ to A₄, and then into line 35 and associated branches. The line 35 conducts the air through T 67, check valve 68, T 80 into line 82. The pressure of air in the associated lines 65 and 78 is effective to hold the check valves 66 and 76 closed so that the flow of nitrogen through the check valve 66 and line 65 is now arrested. The closing of check valves 66 and 76 is effective to force the nitrogen in the line 72 through check valve 74 into the line 36 and its associated branches, and then through the passages B₁ to B₄ of the heat exchanger. After passing through the heat exchanger the nitrogen is then conducted through line 31 and its associated branches into the branch 49 through port 48, chamber 42 and outlet 52. This flow continues until the motor 61 again shifts the valves 54 and 55, thereby to cause the first operating cycle to be repeated, as explained more fully in the aforementioned Collins application.

During the above described cycles the oxygen from the processing apparatus continues to flow into the line 37, passage C and the outlet line 32, although in some instances the oxygen may be collected before passing through the heat exchanger, in which event the center passage C is not used, but such non-use does not interfere with the above described operation.

Use of the heat exchanger of the present invention permits a lengthening of the cycle of the process shown in the aforesaid Collins application, due to the fact that the condensing solids (such as CO₂) tend to collect in the spaces between the plates rather than exclusively along the walls of the passages. Hence there is a less rapid clogging of the passages with condensing solids than when using the exchanger shown in the Collins application.

The heat exchanger 100, shown in the embodiment of Figs. 7 to 14, is basically the same as that of Figs. 1 to 6 and is designed for use in a system similar to that shown in Fig. 1, with the exception that the oxygen passage is eliminated. In this particular design there is provided sixteen fluid passages for the incoming air and sixteen passages for the outgoing nitrogen, a total of thirty-two substantially identical passages arranged in four transversely extending groups.

The heat exchanger 100 comprises a plurality of flat, rectangular perforated plates 101 (Fig. 11) interposed between separators 102 (Fig. 12) formed with transversely and longitudinally extending ligaments 103 and 104 which define the thirty-two fluid passages. Each of the plates 101 may be of copper, aluminum or other suitable material as above noted, and the separators may be of any suitable gasket material exhibiting some degree of deformability.

As shown more clearly in Fig. 13, each of the plates 101 is formed with a plurality of circular holes 105 disposed in transverse rows offset with respect to those in the adjacent rows, and the ligaments 104 have a width exceeding both the diameter of the holes 105 and the center-to-center distance between the holes. Hence, when a plate 101 is interposed between two separators 102, the

ligaments 103 and 104 seal off the underlying openings, as illustrated in Figs. 13 and 14, to provide the fluid passages A₁ to A₁₆ and B₁ to B₁₆, each of which comprises a plurality of regularly interrupted flow channels, defined by the aligned openings 105 and having substantially the same flow characteristics as illustrated in Fig. 6. Since the separators are of relatively compressible material, they may be compressed or deformed so as to interlock with the openings 105 of the plates, as indicated in Fig. 14, thus providing gas-tight seals between the fluid passages. This interlocking also guards against sideways slippage or movement of the plates and separators, which is another advantage which may be derived from the use of the present invention.

A stack of plates 101 with interposed separators 102 constitute the body of the heat exchanger and at each end of the stack there is provided a header or manifold 110 (Figs. 7 to 10). Each header consists of a unitary casting which may be of aluminum, cast iron or a like material. The inner body portion of each casting, as shown in Figs. 9 and 10, is formed with eight longitudinally extending channels corresponding to and aligned with the longitudinally disposed passages of the heat exchanger body. These channels are designated (Figs. 9 and 10) A, B, etc., and communicate respectively with the passages designated A₁ to A₁₆ and B₁ to B₁₆.

The outer body portion of each casting is formed with four compartments 111, 112, 113 and 114, as shown in Figs. 7 and 8, and the wall or web 116 separating these compartments from the channels A, B, etc., is provided with spaced openings 118 (Figs. 8 and 10) arranged so that all the A channels communicate with compartments 111 and 113 and all the B channels communicate with compartments 112 and 114. Thus, the fluid passages A₁ to A₁₆ are interconnected with each other with the compartments 111 and 113; and likewise the fluid passages B₁ to B₁₆ are interconnected and communicate with compartments 112 and 114. The four compartments are provided with closure plates 121 to 124 (Fig. 8) formed with openings by which the compartments may be connected in pairs 111, 113 and 112, 114 by conduits (not shown), thereby providing common inlet and outlet lines for each group of passages.

The assembly of plates 101, separators 102 and headers 110 is firmly clamped together by externally disposed spring-loaded tie-rods 125, the ends of which are connected in any suitable manner with the outwardly extending lateral flanges 128 formed integral with the headers 110, as shown in Figs. 7 to 10.

Where, as here shown, the heat exchanger is designed for use in a system such as illustrated in Fig. 1, the compartments 111 to 114 of the headers 110 may be connected with a valve mechanism and check valve arrangement in a manner corresponding to that shown for the heat exchanger 1.

Referring to the embodiment of Figs. 15 to 18, the heat exchanger 140 is of the non-reversing type, but is designed to secure an additional cooling effect by reason of a water injector. The exchanger 140 comprises a plurality of foraminous plates which may be of the type illustrated in Fig. 17 or Fig. 18, depending upon the contemplated use of the heat exchanger, but in either case the plates are interposed between fenestrate separators 142 formed with ligaments 144 which define three elongate fluid passages A, B and C, the outer passages A and C being for the outgo-

13

ing gas or fluid, e. g., the nitrogen in the system illustrated in Fig. 1, and the central passage B being for the incoming gas, e. g., the compressed air of the aforesaid system.

The plates 141 (Fig. 17) are formed with a longitudinally aligned outer group of rectangular openings 145 and an inner group of longitudinally aligned rectangular openings 146 separated from each other by longitudinal webs 148 corresponding to the ligaments 144, the size and shape of the openings 145 and 146 being designed to insure the most efficient heat transfer consistent with the flow characteristics and thermal properties of the fluids to be treated. The plates 141a (Fig. 18) are substantially the same as those of the embodiment shown in Figs. 7 to 14 and the openings 145a therein and the center-to-center distance between these openings are smaller than the width of the ligaments 144 of the separators so as to permit the fluid passages to be sealed in a manner previously described. It will be noted that with either type plate the fluid passages A, B and C each consists of a plurality of regularly interrupted flow channels having substantially the same flow characteristics as illustrated in Fig. 6.

A stack of plates and interposed separators constitute the body of the heat exchanger and at a point spaced from its warm end, i. e., a point where the temperature of the outgoing gas is above 32° F., there is interposed a water injector 150 (Fig. 16) which comprises a rectangular frame-like member having two longitudinally extending spaced arms 152 and 153, the shape of the upper and lower surfaces of the injector corresponding to that of the separators so as to insure a gas-tight seal when assembled as shown in Fig. 15. The arms 152 and 153 are provided with longitudinally extending ducts 154 and 155 which extend through the end wall 156 of the injector, as shown in Fig. 16. A plurality of spaced minute openings 158 and 159 (here shown on an exaggerated scale) are formed in the outer side walls of the arms and extend at an angle in the direction of the flow of the fluid in the passages A and C.

With this construction and arrangement water admitted through supply lines 161 and 162 (Fig. 15) is discharged through the openings 158 and 159 in the form of a fine spray into the passages A and C, and as the temperature of the gas at this point is above 32° F. and as the gas is relatively dry, the water is quickly vaporized with a consequent cooling of the gas. Thus, an additional cooling effect is produced and as a result the incoming gas in the passage B is cooled to a greater extent than would otherwise be possible.

At each end of the stack there is a header or closure 165 formed with three offset openings respectively aligned with the fluid passages A, B and C and which receive pipe lines 166, 167 and 168, respectively. The stack is held in assembled relation by interiorly disposed spring-loaded tie rods 170 which extend through the fluid passages A and C, passing through the openings in the plates which may, if necessary, be enlarged so as to accommodate the tie rods.

This particular design of heat exchanger is not only useful in a system of the type illustrated in Fig. 1, but also in any system where it is desired to effect a heat exchange between two fluids, at least one of which is a gas to which heat is to be transferred.

In Fig. 19 we have shown a heat exchanger constructed in accordance with the present invention associated with a gas turbine system which

14

provides particularly advantageous application. In this embodiment the heat exchanger 180 may be made from plates and associated separators which may or may not be integral, but in either case the heat exchanger may have either two groups of passages, such as illustrated in the embodiment of Figs. 7 to 14, or a single passage interposed between connected outer passages, as illustrated in the embodiment of Figs. 15 to 18, but in any case the size and shape of the two passages or groups of passages, as the case may be, and the openings in the foraminous plates are designed to secure the desired performance for the particular installation. Because this particular application does not usually require a periodic disassembly of the heat exchanger, the use of the tie rods may, if desired, be eliminated, in which case the assembled parts may be brazed together, as above explained. Since the heat exchanger must withstand temperatures of the order of 500° F. or more, individual separators if used should be of asbestos or the like noncombustible, infusible material, but in any case the foraminous plates, with or without integral separators, may be of cast iron, steel, copper or other suitable material.

The inlet 181 at the cold end of the exchanger is connected by a pipe line 182 to the discharge port of a pump or fan 184 driven by the gas turbine 185, and the outlet 186 of the warm end of the heat exchanger is connected by pipe line 187 to the combustion chamber 188 of the turbine 185. The exhaust port on the turbine is connected by a pipe line 190 to the inlet 191 at the warm end of the exchanger and the outlet 192 at the cold end of the exchanger may exhaust to the atmosphere.

A particularly advantageous feature of this system is that the heat exchanger not only is effective to transfer the practical maximum available heat from the exhaust combustion gases to the incoming air, but furthermore the transfer is accomplished without an objectionable pressure drop in either passage, and the space requirements are particularly low. Hence, a greater over-all efficiency of the system is attained than is possible with heat exchangers of conventional design.

In addition to the advantageous features above noted, it will be observed that a heat exchanger constructed in accordance with the preferred form of the present invention may readily be disassembled for cleaning and repair and easily assembled without the necessity of brazing, welding or soldering the parts. Since both the foraminous plates and separators for any given design are ordinarily identical, they may be economically manufactured and assembled by mass production methods with the assurance that each such unit will have substantially identical performance characteristics, thereby permitting the substitution or replacement of one unit by another in any system without the necessity of making compensating adjustments.

While we have shown and described different desirable embodiments of the invention, it is to be understood that this disclosure is for the purpose of illustration and that various changes and modifications may be made without departing from the spirit and scope of the invention as set forth in the appended claims.

We claim:

1. A heat exchanger comprising a plurality of perforated metal plates of uniform thickness and associated separators assembled into a lam-

inated structure with the corresponding openings in said plates being uniformly disposed to provide predetermined flow characteristics, said separators including ligaments surrounding a plurality of said openings to define a plurality of regularly interrupted fluid passages, headers at the opposite ends of said structure communicating with the passages defined by said ligaments, and means holding said structure and headers in assembled relation.

2. A heat exchanger as set forth in claim 1, wherein the combined area of the openings in each of said plates is approximately equal to the area of the metal about said openings.

3. A heat exchanger as set forth in claim 1, wherein the thickness of each separator is less than that of the associated plate.

4. A heat exchanger as set forth in claim 1, wherein the openings in said plates are of generally frusto-conical shape.

5. A heat exchanger as set forth in claim 1, wherein the holding means comprises spring loaded tie rods extending between said headers for clamping the assemblage together.

6. A heat exchanger as set forth in claim 1, wherein said plates are formed with uniformly spaced openings and said separators are of a deformable material having passage defining ligaments of a width greater than the center to center distance between adjacent openings in said plates, the material of said separators being compressed so as to project into the contiguous openings of the adjacent plates, thereby to provide an interlocking seal.

7. A heat exchanger as set forth in claim 1, wherein the foraminous plates are formed with uniformly spaced openings and said separators are of a deformable material having passage defining ligaments of a width greater than the major dimension of said openings, the material of said separators being compressed so as to project into contiguous openings of the adjacent plates, thereby to provide an interlocking seal.

8. A heat exchanger as set forth in claim 1, wherein said separators are integral with said plates.

9. A heat exchanger as set forth in claim 1,

wherein said separators are integral with said plates and their contiguous portions are formed with complementary interengaging grooves and projections constituting an interlocking seal effective to prevent lateral slippage of the assembled plates.

10. A heat exchanger as set forth in claim 1, wherein said corresponding openings are of substantially the same size and in substantial alignment.

11. A heat exchanger as set forth in claim 1, wherein an injector is interposed between two of said foraminous plates at a point spaced from one end of the heat exchanger, said injector having the same general cross-sectional shape as said separators and being formed with arms corresponding to the ligaments of said separators, one of said arms having a duct communicating with one of said fluid passages for discharging a fluid therein.

12. A heat exchanger as set forth in claim 1, wherein an injector is interposed between two of said foraminous plates at a point spaced from one end of the heat exchanger, said injector having the same general cross-sectional shape as said separators and being formed with arms corresponding to the ligaments of said separators, said arms having ducts communicating through a plurality of fine openings with at least one of said fluid passages for admitting thereto a liquid in the form of a spray.

HOWARD O. McMAHON.
GUSTAVE A. BLEYLE, JR.
RICHARD B. HINCKLEY.

REFERENCES CITED

The following references are of record in the file of this patent:

UNITED STATES PATENTS

| Number | Name | Date |
|-----------|----------|---------------|
| 1,238,574 | Scanes | Aug. 28, 1917 |
| 1,631,141 | Lorenz | June 7, 1927 |
| 1,734,274 | Schubart | Nov. 5, 1929 |
| 1,863,586 | Wilke | June 21, 1932 |
| 2,096,272 | Young | Oct. 19, 1937 |
| 2,278,242 | Chapman | Mar. 31, 1942 |