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[54] PROPERTY INTERCHANGE SYSTEM FOR FLUIDS

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[52] **U.S. Cl.** **165/166,** 161/133

[51] **Int. Cl.** **F28b 3/12**

[58] **Field of Search** 165/166, 5, 10, 4; 156/207, 208–211

[56] **References Cited**

UNITED STATES PATENTS

2,173,815	5/1937	Slisz et al.	156/207 X
2,429,482	10/1947	Munters	156/208
2,553,030	5/1951	Bell	165/166
2,602,645	4/1948	Benenati et al.	165/4
2,812,165	11/1957	Hammond	165/166
3,081,822	3/1963	Wolansky et al.	165/10
3,165,152	1/1965	Jones	165/166
3,212,572	10/1965	Otto	165/166
3,256,930	6/1966	Norback	165/166 X
3,305,010	2/1967	Campbell et al.	165/166
3,334,399	8/1967	Teeguarden	165/166 X
3,444,925	5/1969	Johnson	165/166
3,449,157	6/1969	Wandel	156/210
3,451,473	6/1969	Urie et al.	165/166
3,490,523	1/1970	Esmond	165/166

FOREIGN PATENTS OR APPLICATIONS

1,106,660	3/1968	Great Britain	165/10

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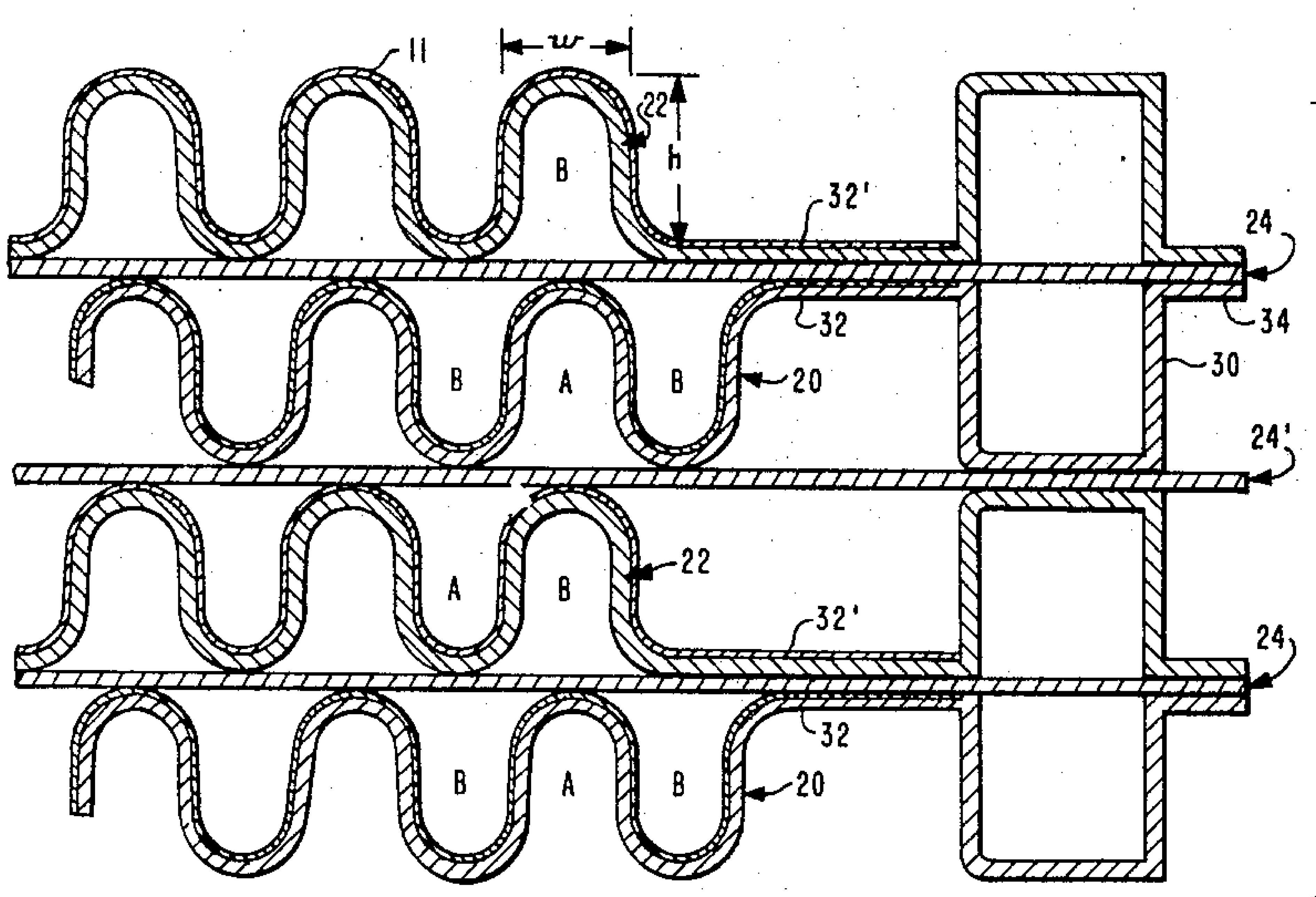
[57] **ABSTRACT**

A system is provided for interchanging properties such as thermal energy, ions or particles, between fluids, such as liquids or gases. Two fluids flow in countercurrent fashion along small, densely packed passageways within an assembly of individual thin plastic membranes formed into a compact multilayer laminate. Standardized membranes are utilized that are self supporting and unite into an assembly that maintains its structural integrity under high thermal stresses. The membrane configurations dispose the individual passageways in selected relation, maintain the fluids separate, and automatically direct the fluids into and out of the passageway system. The flow passageways for different fluids are interspersed so that the fluid within each small passageway is substantially completely encompassed by flowing volumes of the other fluid and property interchange takes place in three-dimensional fashion directly through the passageway walls. High heat transfer coefficients and total heat transfer efficiency are achieved with low fluid pressure gradients by the use of straight, short laminar flows within the small passageways. Limitations imposed by nonuniformities in flow between the passageways are overcome by means for lateral integration of the property states existing in selected passageway sets.

13 Claims, 12 Drawing Figures



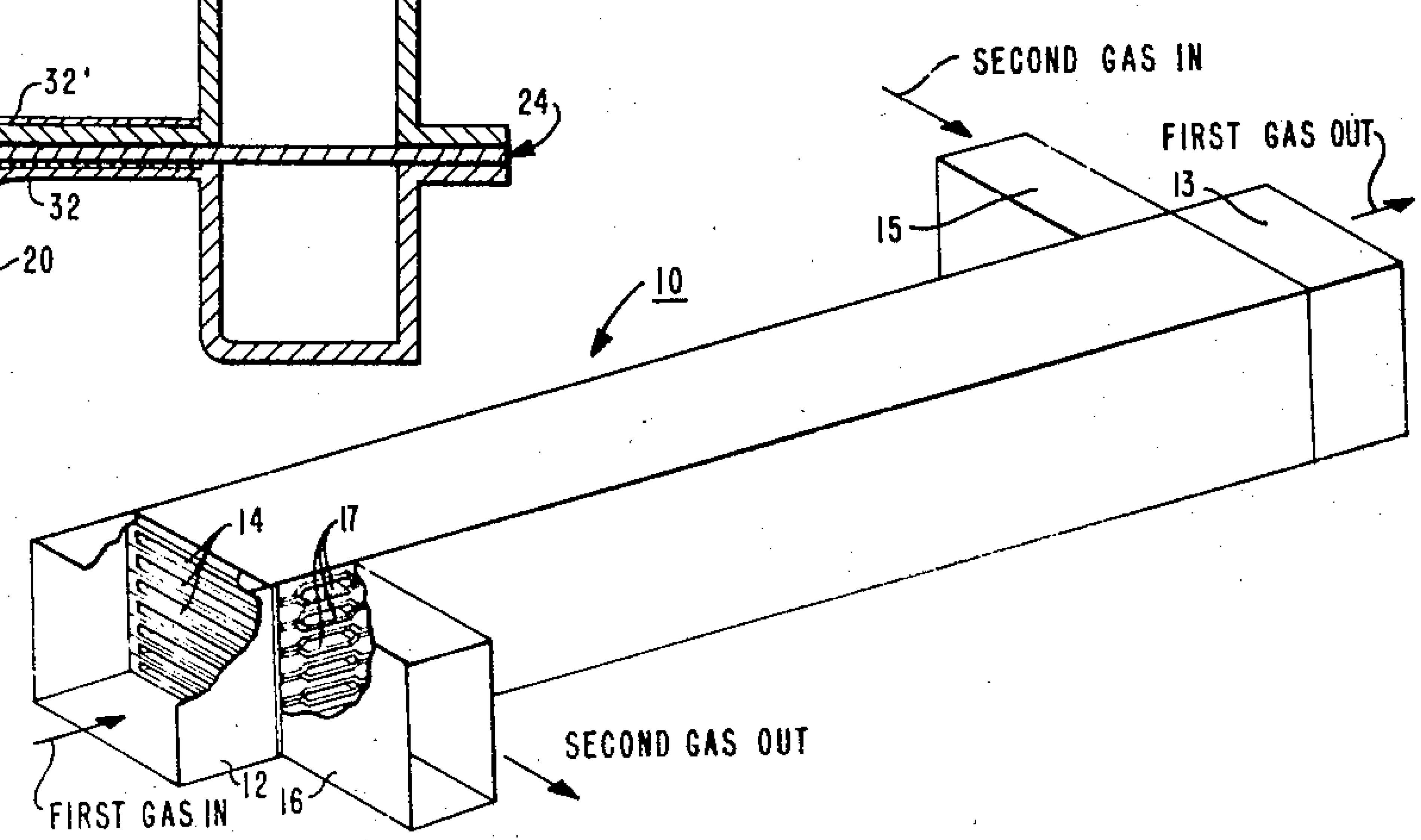
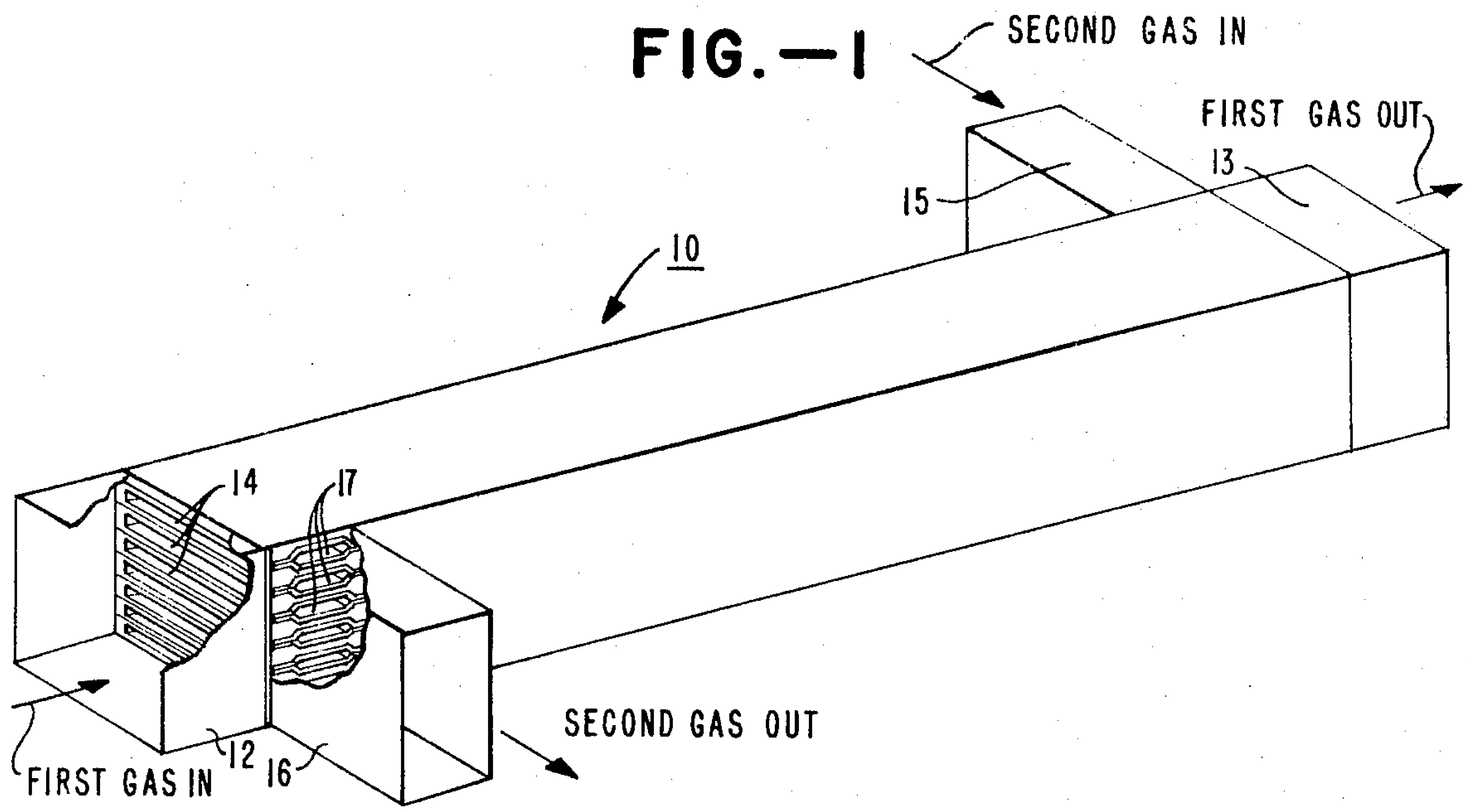


FIG.—1



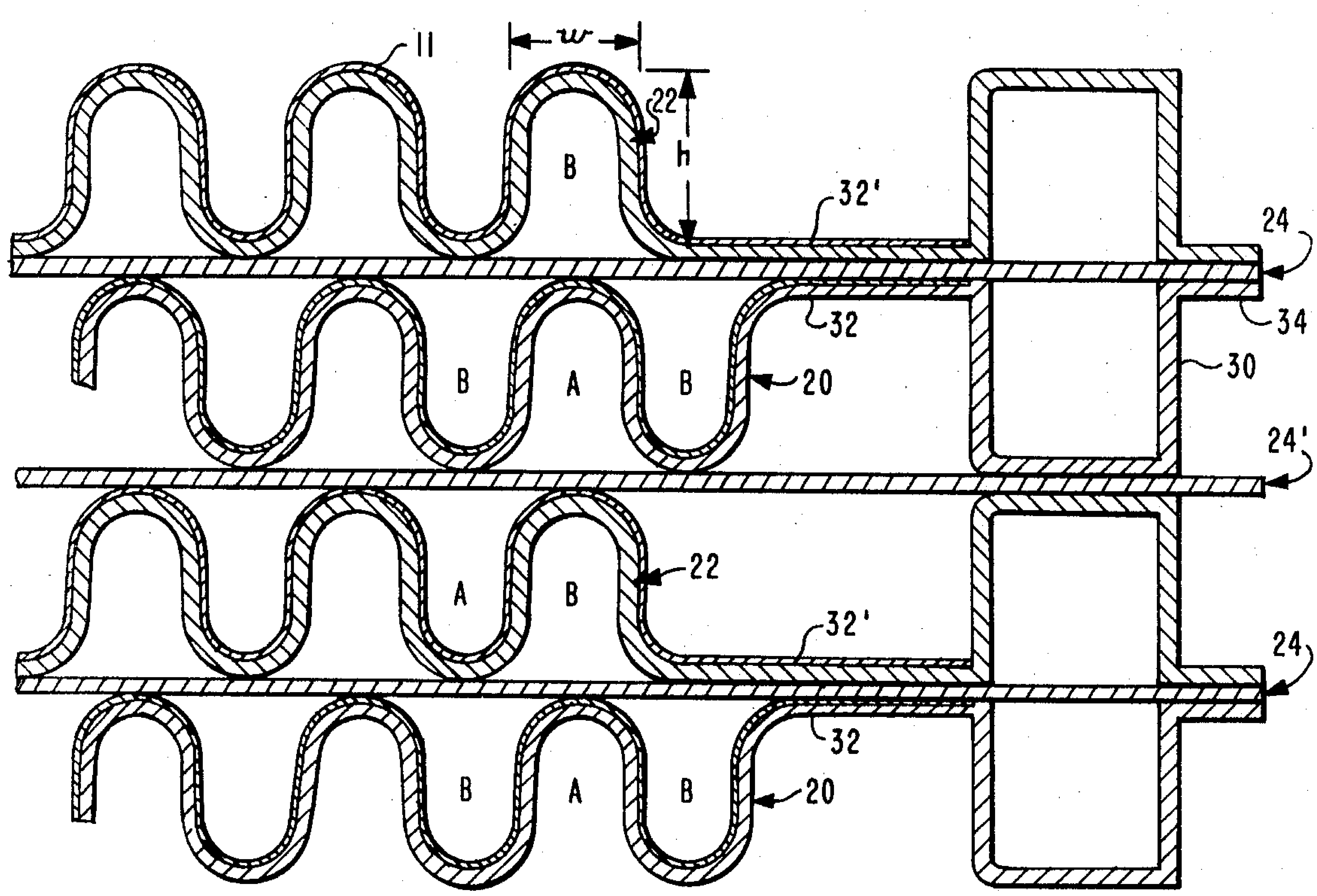


FIG.—2

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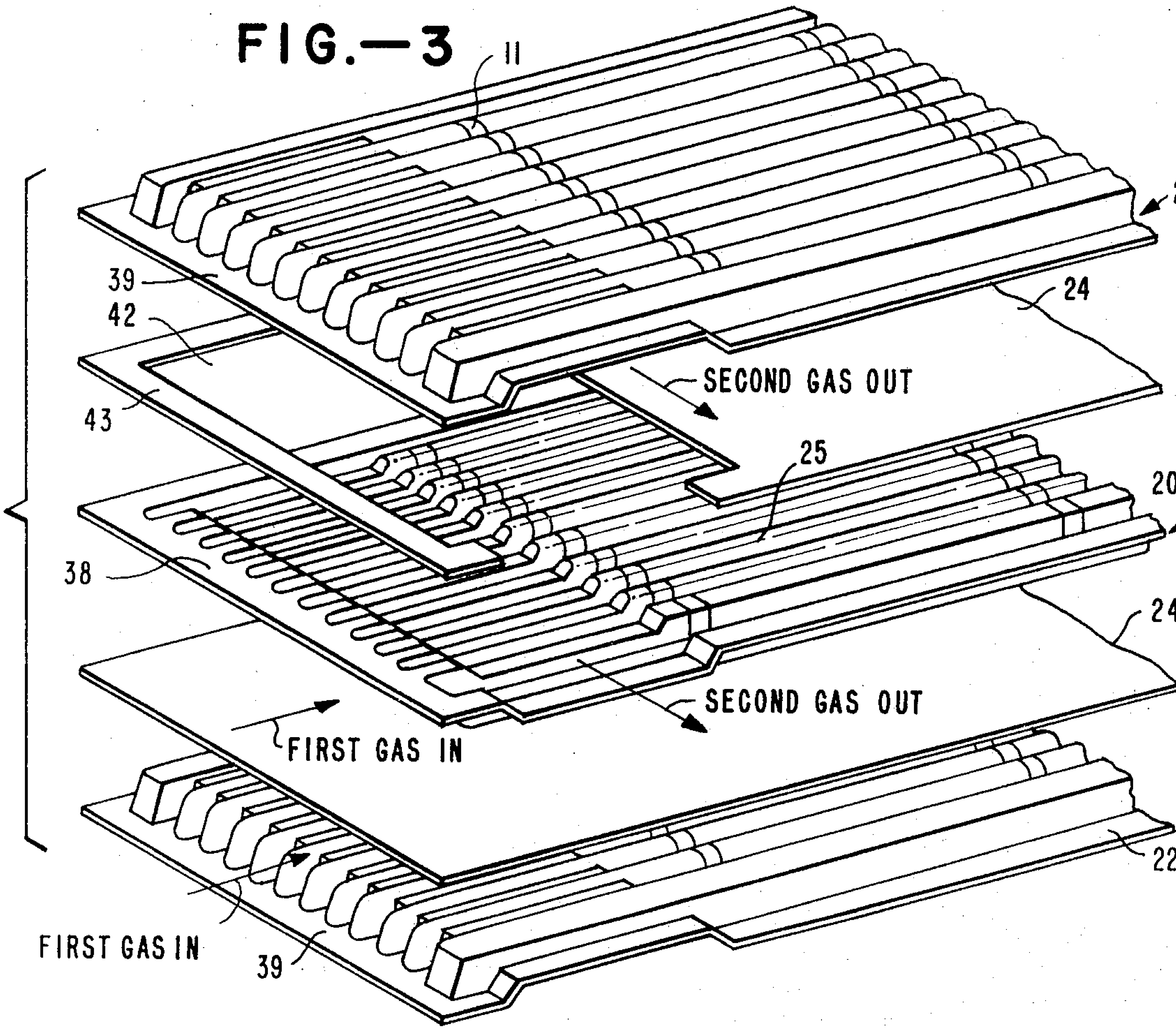
FIG.—3



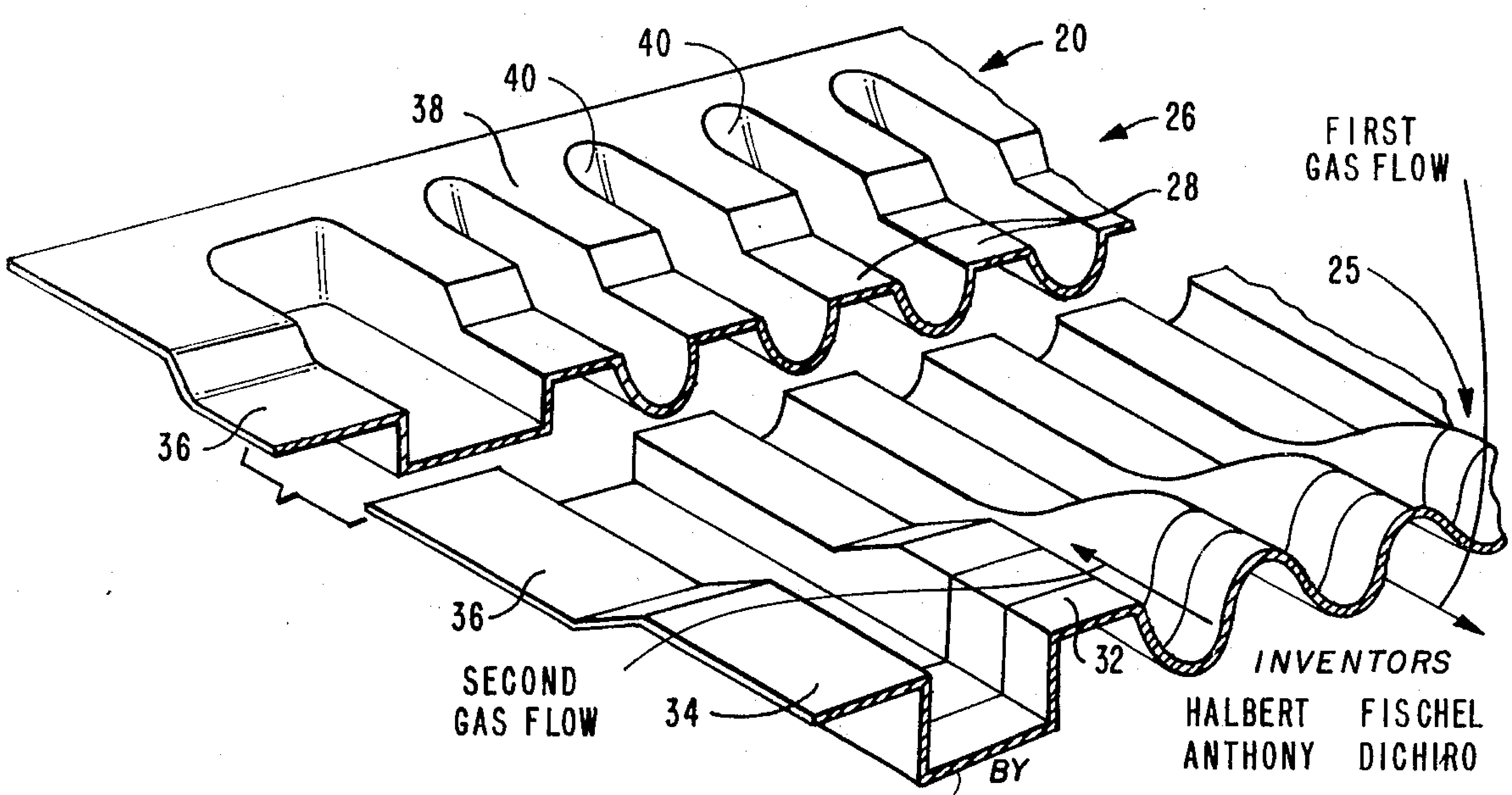


FIG.—4

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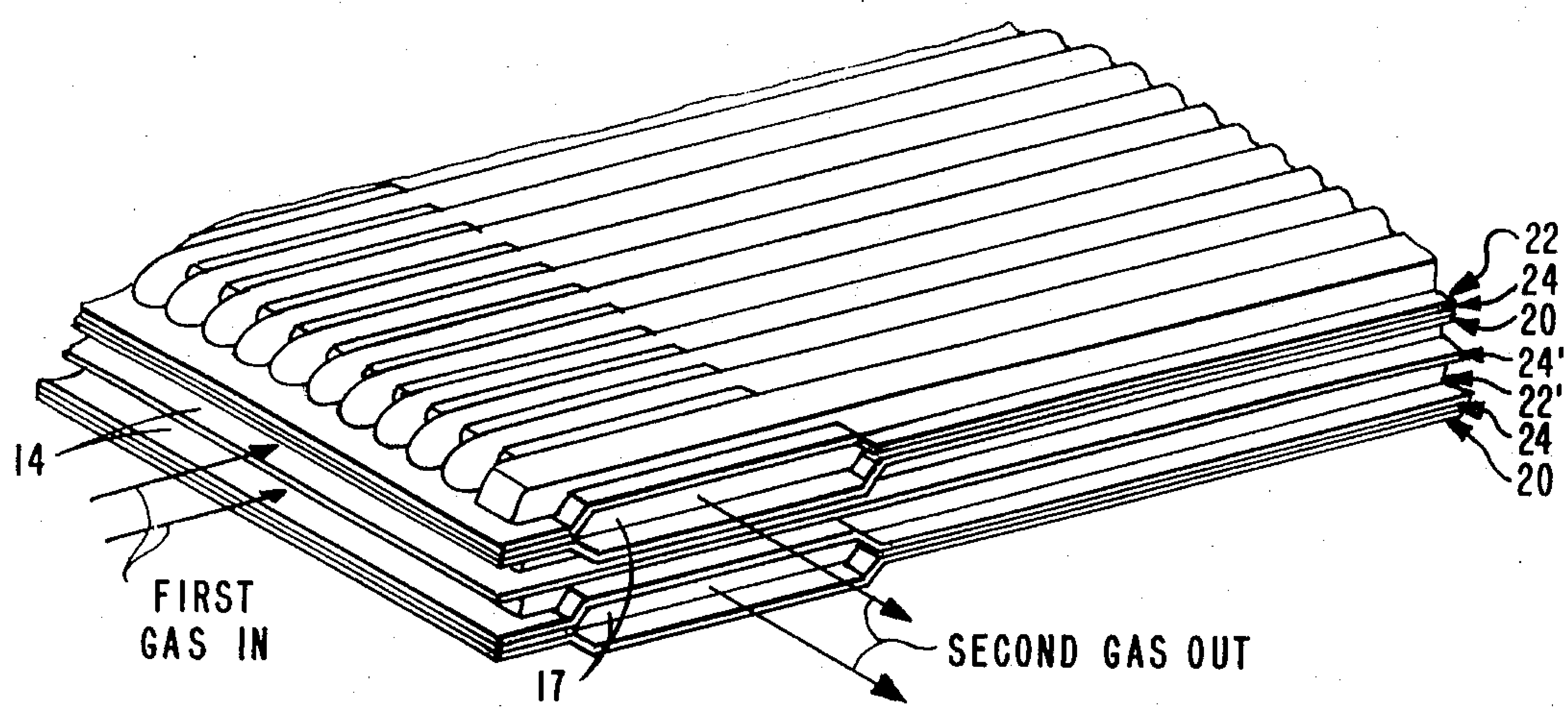

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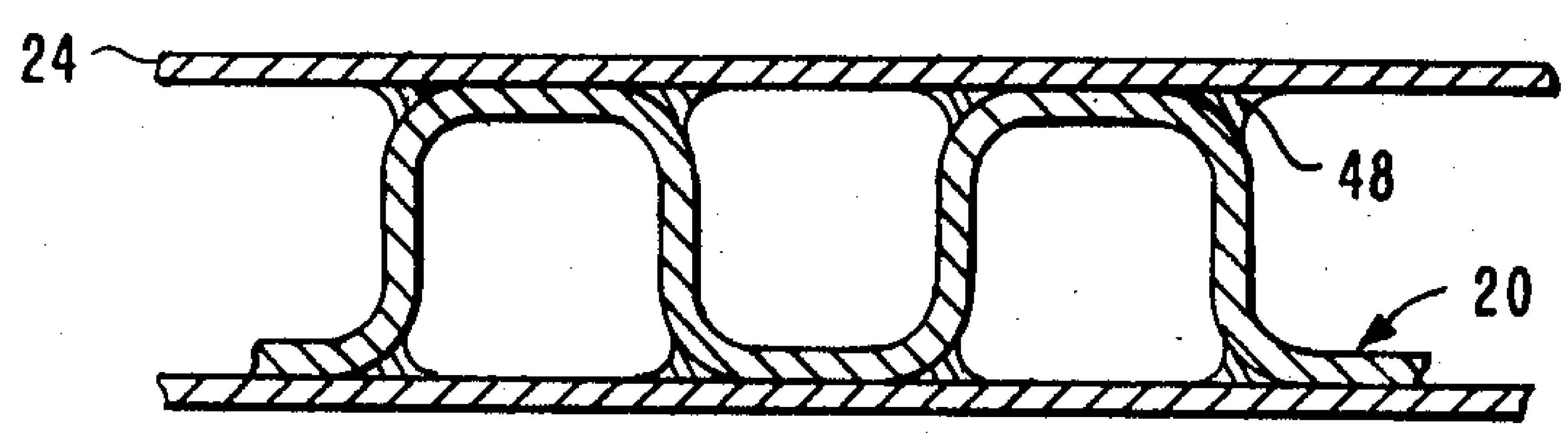

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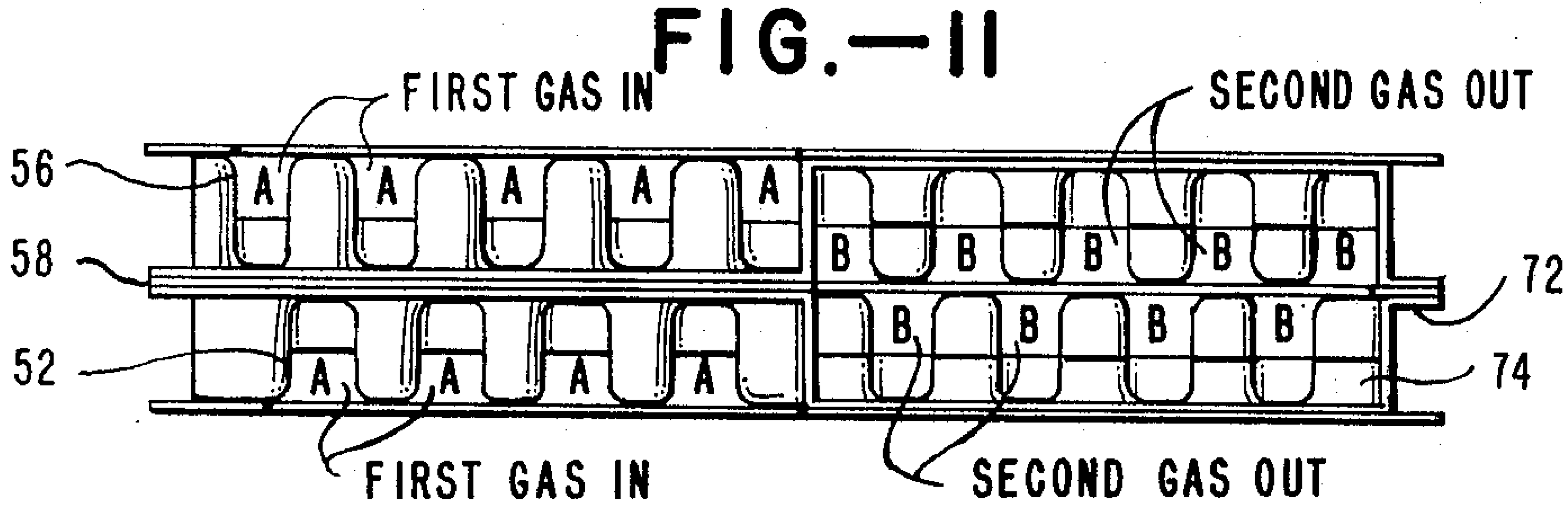
FIG.—11



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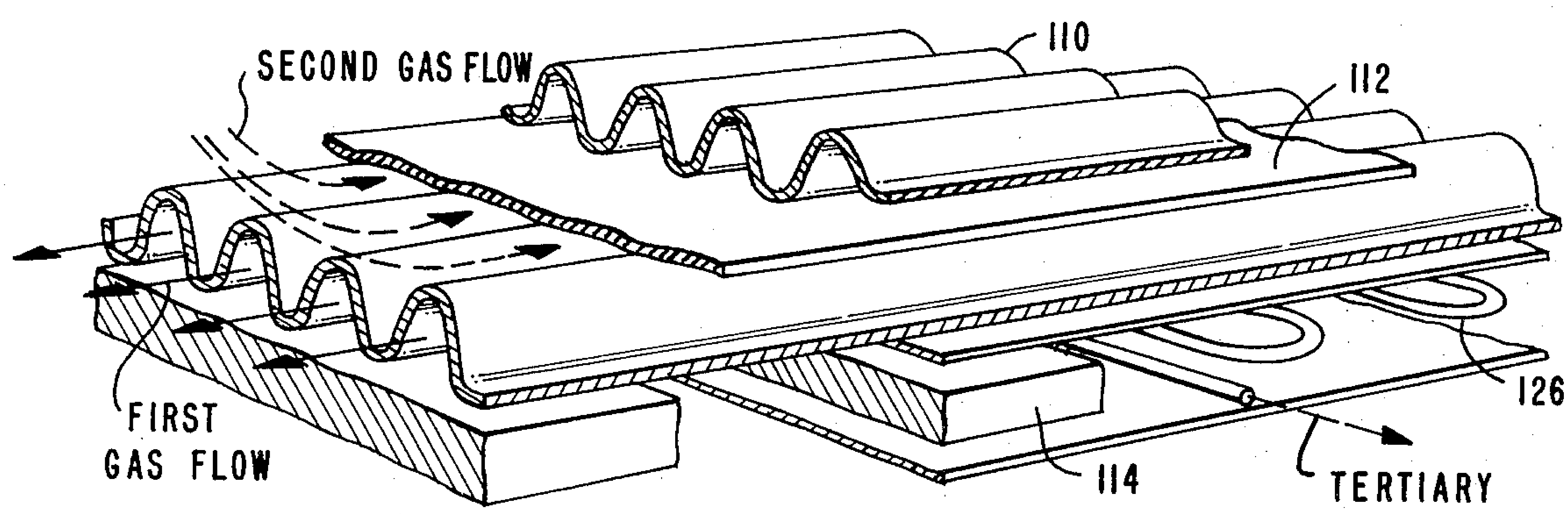

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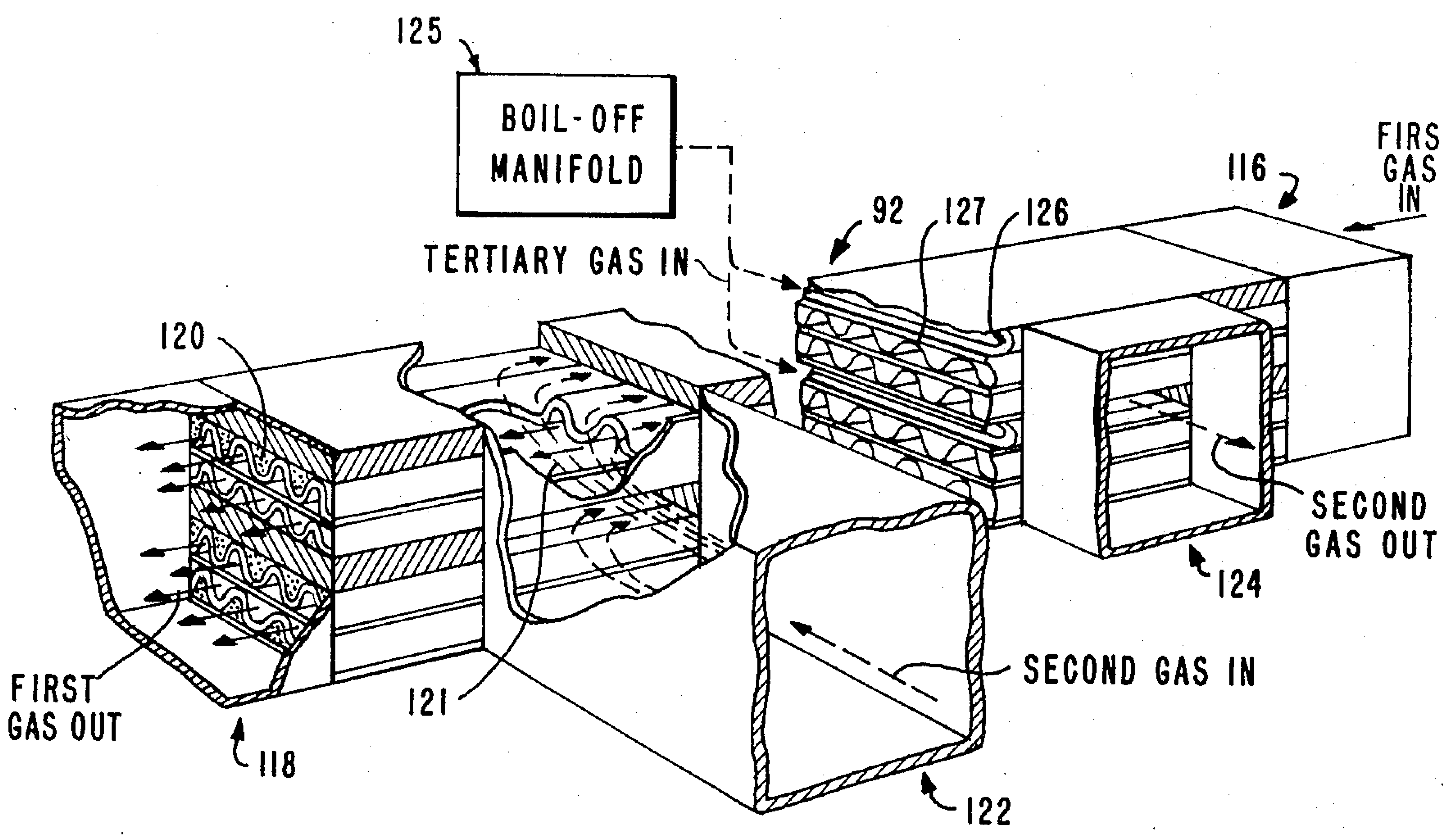

FIG.—7

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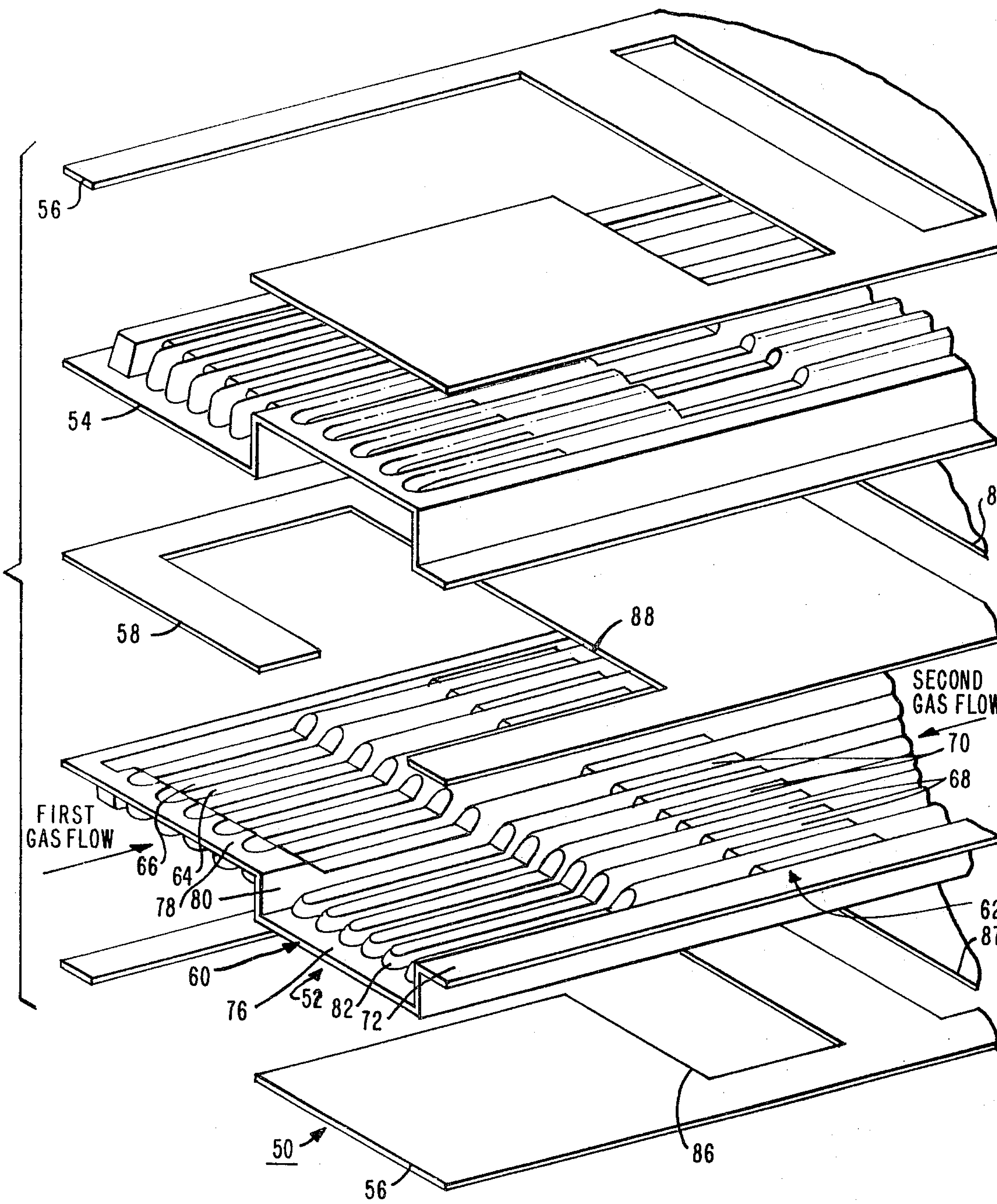

FIG.—9

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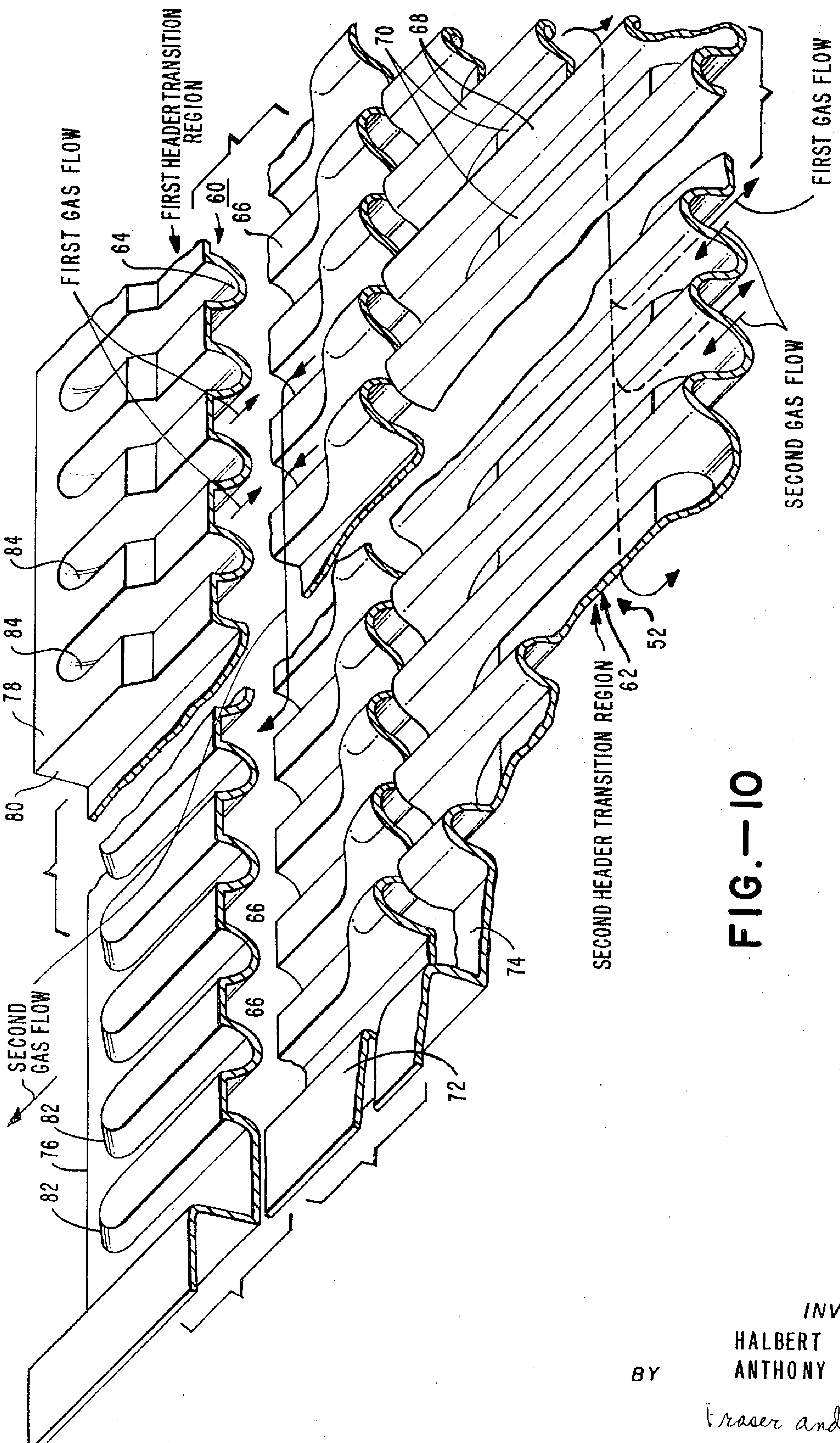

FIG.—10

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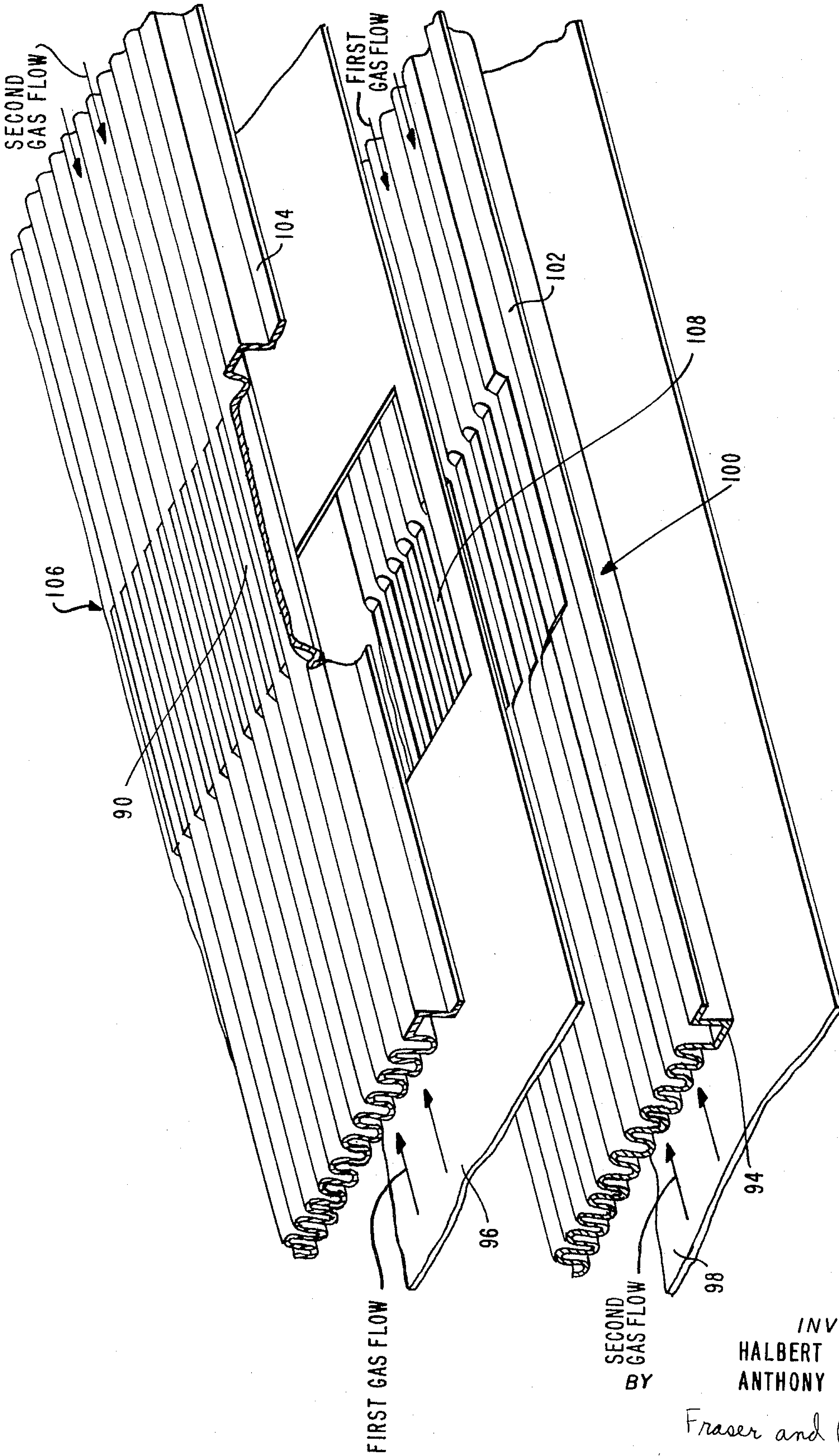

FIG.—12

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PROPERTY INTERCHANGE SYSTEM FOR FLUIDS

BACKGROUND OF THE INVENTION

This invention relates to systems and devices for passing two or more fluids in energy, particle or chemical interchange relationship, and more particularly to high efficiency, compact and inexpensive heat exchangers.

The expression "property interchange systems for fluids" as hereafter used is intended to encompass both gas and liquid flow systems in which chemical, physical, macroscopic, microscopic or molecular exchanges or interactions take place between otherwide separated flowing gases or liquids.

In virtually all existing systems in which a property interchange is effected between fluids, some substantial degree of improvement is possible in terms of operating characteristics or cost factors. In counter-flow heat exchangers, for example, low cost is generally considered incompatible with high heat transfer coefficient and temperature exchange efficiency, a concept given quantitative definition below. Temperature exchange efficiency is one important aspect of exchanger performance and is used hereafter to provide a qualitative reference for discussion and understanding. As discussed generally in the book "Compact Heat Exchangers," 2nd Edition, by W. M. Kays and A. L. London, published by McGraw-Hill Book Co., N. Y. (1964) at page 15, temperature exchange efficiency (sometimes simply T.E.E. herein), is determined by:

T.E.E. = $1 - \beta T/\Delta T$ where ΔT = the difference between the temperatures of two fluids at one end of an exchanger after interchange has taken place, and

ΔT = the total temperature range through which the fluid is taken between ends of the exchanger.

A value approaching unity thus connotes high performance, but it must be recognized that the exchange efficiency value does not provide a fully definitive expression of performance because flow rate must also be considered, as is pointed out in more detail below. Nonetheless, the same basic relationship, given any assumed flow rate, provides a comparative measure that is useful whether evaluating exchange of temperature (as above) or other properties.

Where extremely high temperature exchange efficiency is needed, it is now generally necessary to use extremely long heat exchange path lengths, convoluted paths and multiple passes of fluids through the system. Expensively fabricated structures, generally made of metal for high heat conductivity, are employed together with complicated headers or manifolds. Multiple passes and large flow differential pressures are usually needed to obtain efficiency values of the order of 0.98 and above.

Existing types of high efficiency systems have one or more of several additional disadvantages. Thermal gradients within the fluids themselves limit efficiency unless passageway areas are small or turbulence is introduced. A finely divided passageway system is generally achieved only at substantial increases in cost and complexity of both the heat exchanger and the headering portions of the system. The introduction of turbulent flow tends to markedly increase pressure gradients and reduce flow rates.

In addition, a short, efficient and high flow countercurrent unit has a sharp thermal gradient along its length. Heat therefore tends to flow longitudinally along the separator walls, to an extent dependent upon the thermal gradient, and this longitudinal heat conduction often imposes its own limit on total heat transfer efficiency. High thermal gradients also introduce substantial thermal stresses which cannot readily be withstood without the use of high strength, massive parts. The use of such parts, however, limits efficiency. The efficiency of existing systems is also diminished by non-uniformity of flow distribution within the various passageways, due to membrane distortion and small variations in passageway cross section. These factors become extremely significant when very high efficiencies (e.g. in excess of 0.95) are sought to be attained.

It is generally preferred, in order to obtain high property interchange efficiency values, to flow the fluids whose properties are to be interchanged in countercurrent relationship, and to obtain a high ratio of transfer area to flow volume. With the widespread use of closed cycle cryogenic systems, for example, there is a need for heat exchangers which can effectively conserve refrigeration power or a cryogenic supply. Mobile versions of such systems generally must be very small, have high efficiency and in some instances should introduce only a low pressure gradient. It has not heretofore been considered feasible to satisfy all the mentioned physical and performance requirements simultaneously.

Significant additional problems are also presented by the need for appropriate manifolds or headers for feeding fluids to, and receiving fluids from the separate flow paths. Small and numerous passageways can improve the interchange efficiency but disproportionately increase the costs of the header mechanism. The costs and complexities of header systems have been major factors in limiting the use of countercurrent flow systems. Attempts have been made to utilize plastic elements for property exchange functions because their initial and fabricating costs are low. Such units have, however, been relatively complex, intended only for limited applications, and have moreover provided only relatively low transfer efficiency values.

The interchange of thermal energy between fluids through a membrane has counterparts in many other systems, such as those which interchange particle matter, ionic matter or chemical constituents. In dialysis and oxygenator systems, for example, one liquid substance such as blood may be passed on one side of a suitable membrane while a glucose, plasma, saline or other solution is passed on the other side of the mmembrane. Impurities are drawn into the solution from the blood, thereby purifying the blood. A countercurrent relationship is useful for such systems, in order to achieve high efficiency in extraction of impurities. The requirement that there be an extremely high interchange area to liquid volume relationship also obtains, but in addition critical requirements are imposed on the handling of the blood. Blood is a sensitive tissue-like member that cannot be subjected to thermal shock, mechanical trauma, or substantial differential pressures and consequently the pressure gradient must be very low throughout the entire interchange system. The same desirable features are sought for other property interchange systems for fluids, including gas-liquid systems and dual gas systems.

SUMMARY OF THE INVENTION

A system for interchanging properties of different fluids with high efficiency is provided by an assembly of thin membranes stacked in multilayer laminate fashion. Small corrugations define small longitudinal passageways for fluids on opposite sides of the membranes, each passageway for one fluid being substantially surrounded by passageways for the other fluid and property interchange taking place directly through the thin walls. The corrugations in the membranes define approximately square cross sections, and are displaced between adjacent layers to closely approximate a checkerboard disposition. In some of the heat exchanger exemplifications of the invention, the walls have low thermal conductivity but are so thin that they do not interpose a significant thermal barrier between adjacent fluid segments. Extremely high ratios of interchange surface area to total fluid volume, thin-walled membranes, and optimum and intimate interspersion of laminar-flow fluids in a great multiplicity of small passageways result in temperature interchange between the two fluids with high heat transfer coefficient, without substantial pressure drop.

A feature of the invention is the disposition of a matrix of minute passageways for countercurrent flowing fluids in such fashion as to achieve virtually optimum three-dimensional transfer effects. Each passageway has a height to width ratio of approximately 1:1, with the passageways within separate laminate layers being precisely positioned. Each column of fluid is surrounded by columns of the countercurrent fluid. Passageway densities in excess of several thousand per square inch of cross section are readily achieved, although the internal fluid volume still occupies a high proportion (e.g., in excess of 80 percent) of the total interchange volume. There is also an extremely high ratio of transfer area to unit volume, this being in excess of 100 in^2/in^3 in one practical example.

In accordance with the invention the property states of fluids in separate lines of flow may be equalized or integrated to minimize the effects of flow rate differences arising from dimensional and other variations. Such integration may be realized in a heat exchanger having membranes of relatively low heat conductivity by strips intersecting lines of flow and transferring heat between separate passageways. In one exemplification a number of lateral conductive strips are spaced apart along the length of the structure. Alternatively, longitudinally separated internal header regions may be spaced along the flow paths to physically mix flows from individual pasageways in selected regions. Elongated lateral apertures may be incorporated at various regions within spacers between the membranes to allow periodic physical mixing for the same purpose. Alternatively or in addition, integration may be effected by inducing turbulence within flow paths by roughening the sides of the corrugations in contact with the flows, for example. These means may be used separately or together in varying cpmbinations.

Further in accordance with the invention, particular membrane and header configurations may be utilized to overcome the mechanical, cost, and volume limitations of the prior art. In a specific example, very thin plastic membranes are thermoformed to incorporate central corrugated regions and peripheral support and seal portions. The corrugations are small periodic variations of generally undulating section, there being as many as fifty or more corrugations per inch in typical practical examples. The membrane structures also define header transition regions, preferably by virtue of the shapes of the membranes themselves, communicating with both the internal passageways and external headers. Planar support elements may be alternated with corrugated membranes within the laminate to unify and rigidify the structure against thermal stresses. The support elements are preferably bonded to the nodes of the corrugations internally, as well as along selected regions of the periphery. Because of the thin pliant nature of the membranes, and the physical integrity of the assembly, temperature differences of several hundred °C over a little more than a foot in length have been realized without adverse effects on structural or operative properties.

In one example in accordance with the invention, only two standardized types of corrugated plastic membranes together with alternate flat membranes are employed in forming an assembly. Each corrugated membrane includes a central corrugated region, peripheral lip portions at the sides and end, header transition regions adjacent the ends, and selected depressed surfaces in the peripheral lip portions adjacent each end. In the header transition regions, the membrane deviations are only on one side of the median plane for the membrane, permitting at least partially transverse flow across the membrane. The first and second types of membranes are essentially mirror images, such that between first alternate pairs the header transition regions and the depressed surfaces in the peripheral lips face each other to define internal header transition volumes communicating with first peripheral apertures. Between the alternate pairs, however, peripheral apertures are disposed across each end and spaced apart from the first apertures. The header transition regions provide communication between the associated internal passageways and first peripheral apertures, whereas the other internal passageways communicate directly with the peripheral apertures disposed across the end. Diifferent headers coupled to the sets of corresponding apertures provide inlets and outlets for the fluids.

The internal header transition regions typically are defined by half-height areas in the corrugated portions of two facing mirror image membranes. One or more of such membranes may be utilized, and they communicate with end headers or side headers. Thus the exchanger design may utilize, at a given end, two adjacent end headers, two side headers, or various combinations of these. In the header transition regions the longitudinal flows are at least partially transversely directed toward the appropriate headers, without the introduction of a significant pressure drop.

Property exchange systems in accordance with the invention may be advantageously fabricated by thermoforming in a controlled heating cycle using matched molds, and assembling the membranes together with interposed support sheets in bonded relation by spraying the facing surfaces with an adhesive mixture, and assembling subunits into a complete body while maintaining desired alignments.

BRIEF DESCRIPTION OF THE DRAWINGS

A better understanding of the invention may be had by reference to the following description, taken in conjunction with the accompanying drawings, in which:

FIG. 1 is a perspective, partially broken away, view of a property interchange system in accordance with the invention;

FIG. 2 is an enlarged simplified cross sectional view of a central portion of the interchange system of FIG. 1;

FIG. 3 is an enlarged exploded simplified view of a portion of the assembly of FIG. 1;

FIG. 4 is an enlarged perspective view of an end fragment of one corrugated membrane of the arrangement of FIG. 1;

FIG. 5 is a fragmentary perspective view of one corner of the interchange system of FIG. 1, showing the fluid flow paths in greater detail;

FIG. 6 is an enlarged cross sectional view of the relationship of individual corrugations in the system of FIG. 1;

FIG. 7 is a broken away perspective view of a second property interchange system in accordance with the invention;

FIG. 8 is an enlarged fragmentary view of a portion of the system of FIG. 7;

FIG. 9 is a simplified exploded view of a portion of a third property interchange system in accordance with the invention;

FIG. 10 is an enlarged fragmentary view of a portion of a membrane employed in the system of FIG. 9;

FIG. 11 is an end view of an assembly comprising the portions of FIG. 9; and

FIG. 12 is an exploded perspective view of a portion of membranes and spacers used in a different arrangement in accordance with the invention.

DETAILED DESCRIPTION OF THE INVENTION

A property interchange system for fluids, referring now to FIGS. 1–5, comprises a heat exchange system for gases that are to be oppositely shifted in temperature between limits which lie in the ambient range at one extreme and in the near-liquid nitrogen range at the other extreme. For many closed cycle cryogenic applications, conservative use of refrigeration capacity requires a highly effective heat interchange, although it is also generally desirable that the exchange unit be compact, inexpensive and readily fabricated. Such needs are typified by closed circuit, self-contained underwater breathing apparatus using cryogenic fluids.

The system illustrated in FIGS. 1–5 fulfills all of these functions and further maintains its structural and operative integrity even though the opposite ends of the unit may be maintained at a temperature differential substantially in excess of 200°C. As previously discussed, however, a heat exchanger is merely one example of applications of the concepts of the invention.

As best seen in FIG. 1, the heat exchanger 10 comprises a generally rectangular central body with a set of inlet and outlet headers or manifolds. The principal gas flow paths along the central interchange volume within the exchanger 10 are parallel to its longitudinal central axis. The inlet and outlet headers may, as will be evident hereafter, be widely varied in size, shape and position, or reversed in function. For purposes of illustration, however, an inlet header 12 and an outlet header 13 for a first gas are disposed at opposite longitudinal ends of the exchanger 10, coaxial with the central axis and communicating with slot-like apertures 14 in the ends of the exchanger 10. An inlet header 15 and an outlet header 16 for a second gas communicate with slot-like apertures 17 adjacent different ends and on opposite sides of the exchanger 10. The first gas, here assumed for purposes of illustration to be at or near ambient temperature, thus passes directly along the length of the exchanger 10 between the inlet header 12 and the outlet header 13, whereas the second gas, assumed to be initially at near-cryogenic temperature (e.g. liquid nitrogen), passes from the inlet header 15 transversely into the interior of the exchanger 10, then passes along the length of the exchanger 10 in a direction opposite to the first gas until approximately abreast of the outlet header 16, at which region it is diverted transversely out into the outlet header 16 through the apertures 17.

Within the interchange volume in the generally central region of the header 10, the two gases pass in intimate countercurrent flow realtionship in a manner illustrated in enlarged form in FIG. 2. The first gas (designated A) and the second gas (designated B) are separated vertically into alternating thin sheet-like volumes or passages which are also separated transversely by the corrugations into small spaced passageways. The passageways for the type A gas are alternated with passageways for the type B gas, as shown in FIG. 2. This construction is achieved by deploying a multiplicity of corrugated membranes in multi-laminate fashion, with precise alignment of corrugations between layers. Although for forming purposes the corrugations or undulations are generally sinusoidal in form as shown in FIG. 2, it will be appreciated that the terms "corrugations" or "undulations" are used for convenience and for ready visualization and that in fact any of a wide variety of shapes incorporating deviations from the principal membrane plane may be employed. For example, the membrane may include ridges and grooves that deviate from a central plane in bidirectional fashion, or ridges which simply deviate in one direction. The deviations may be periodic or aperiodic and may be curvilinear or rectangular in shape. Lateral heat transfer between the flows in the separate passageways is achieved by means of the heat conducting strip 11 in FIG. 2, as is described in greater detail hereafter.

The relationship and construction shown in FIG. 2 provide a highly effective heat interchange configuration. A plurality of corrugated membranes 20, 22 of first and second types respectively are disposed in alternating fashion through the height of the exchanger 10. Planar support membranes 24 are interposed between each pair of membranes 20, 22. The first and second types of corrguated membranes 20, 22 have minute corrugations lying in in-phase relationship. The distinction between the two types is primarily in a mirror image relationship useful in forming the complete laminate and described in greater detail below.

The cross sectional areas within the passageways designated A and B are extremely small, as are the corrugation height, designated by h, and the corrugation width, designated by w. In one practical example, the dimensions h and w are approximately in a 1-to-1 ratio, and each is approximately 0.020 inches, so that there are approximately 50 corrugations per inch. As can be seen in FIG. 2, each passageway containing an A gas is substantially surrounded by passageways containing the B gas, and vice versa. This checkerboard-type pattern (as viewed in vertical section through the core of the exchanger) is dependent upon the maintenance of the inter-laminate alignment as well as relatively straight-sided passageway shapes. Transfer of properties takes place directly through the wall of a membrane **20** or **22**, in a direction normal to the wall thickness. The in-phase relationship between the corrugations in successive layers is important to achieving true three-dimensional property interchange in all radial directions relative to the center of a passageway. Extremely thin membranes are employed, those in this example being of the order of 0.002 inches in thickness. The passageways are so small and the walls so thin that interchange of properties readily takes place between fluids on opposite sides of the passageways. The heat transfer area presented between the counter-flowing gases is greatly extended by the corrugations in the membranes and the area has an extremely high ratio to the confined volumes of gases. In the practical example being discussed, there is a ratio of about 100 in^2 of transfer for each cubic inch of volume. Further, over 80 percent of the total volume is devoted to fluid flow. The exchanger thus comprises a dense matrix of passageways, having in excess of about 250 passageways per square inch, and as many as several thousand passageways per square inch.

Consequently, it is feasible for the first time to utilize low cost plastic heat exchange elements in achieving extremely high temperature exchange efficiency. Another advantage is that the exchanger body **10** of FIG. **1** may be extremely short, such as approximately fifteen inches in overall length, yet operate through an approximately 200° C. temperature differential between the opposite ends without significant loss of efficiency due to longitudinal conduction. Temperature gradients in excess of 10°C. per inch, and as many as about 20°C. per inch, have been realized. A significant further advantage is derived from the fact that the short length of flow, the multiplicity of flow paths and the use of laminar flow introduce only a minimum pressure gradient.

An added important advantage comes from the presence of the conducting strips **11**, which facilitate lateral temperature integration of the separate flows. The significance of such integration is based on the followiing considerations. Uneven mass flow between adjacent flow paths results in temperature differentials between them, varying approximately directly with the difference in mass flow between the flow paths. The resulting temperature imbalance repeated for many different paths has a net effect of causing larger temperature differences at the ends of the heat exchanger between entering and exiting gases than in the case of perfectly uniform flow. This heat differential due to non-uniform flow imposes an upper limit on temperature exchange efficiency differing by a second order quantity from 100 percent. A variation of 1 percent, for example, in passage diameter, which results in a 4 percent imbalance in respective mass flows, makes it impossible without some form of integration to achieve greater than 96 percent temperature exchange efficiency in practice.

In order to minimize the effects of inequalities, a multiplicity of separate heat conductive strips **11** are affixed to the plastic membranes **20, 22** at various regions along the length of the heat exchanger and extend in a continuous band across the width of the membranes. Heat is thus conducted transverse to the longitudinal axis of the heat exchanger between the separate passageways. Longitudinal heat conduction is not significantly affected, because the strips **11** are separated by substantial distances in comparison to their longitudinal dimension. This lateral integration function suppresses the effects of non-uniform flow distribution, raising the upper limit of overall heat transfer efficiency for given dimensional and flow tolerances. A fuller exposition of the problem may be found in an article in *Advances in Cryogenic Engineering*, Volume 12, Plenum Press, 1967, entitled "The Effects of Flow Distribution in Parallel Channels of a Counter Flow Heat Exchanger," by R. B. Fleming, Page 352.

It should be noted that the lower face of one membrane and the upper face of the adjacent membrane completely confine one particular gas. The planar support membranes **24, 24'** are not required for gas separation, but assist in preserving the physical relationship of the elements of the system under the stresses introduced by a sharp temperature gradient along the exchanger **10.** It is preferred for temperature stability, physical properties under low temperature conditions, and forming properties to use a thermoformable material such as a polycarbonate resin in the form of a prestressed thin film, an example of which is sold by General Electric Company under the trademark "LEXAN."

The planar support membranes **24, 24'** need not be used if the corrugations are suffficiently rectangular to prevent one corrugated membrane from nesting within the adjacent membrane. The contacting linear surface between adjacent corrugated membranes may then be bonded, if desired.

Materials used for the conductive strips **11** are of standard heat-conductive type, such as aluminum or copper, and may be vacuum deposited or affixed as a film. In addition, it is preferred to bond the nodal points of the corrugations to the abutting surfaces of the planar support elements **24**, as is more fully described below.

The longitudinal dimensions and number of conductive strips **11** may be increased to include the case in which the entire interchange area of a membrane has a thin heat conductive coating. Such a result is permissible in some applications, in which the adverse effects of longitudinal conduction are more than offset by the beneficial effects of lateral integration. Bearing in mind that small passageways having thin walls are utilized, the membranes may in fact be of a good heat conductor material for some applications.

It will be recognized that heat exchangers of the regenerator type use corrugated membranes interspersed between planar members, and that heat exchangers of other types, such as the crosscurrent type, also use a multiplicity of laminates with corrugations disposed between planar elements. In regenerator-type systems, however, all passageways confine the same fluid at a given time, the membranes alternately taking heat from one gas and giving it up to another. In prior art heat exchangers, the corrugations are utilized primarily to extend the conductive area of an element which additionally provides support, with the gases being separated by the planar elemments. Where fluids have been passed on the opposite sides of a planar separator, high effectiveness has not been achieved and the units have been large and cumbersome.

In this first example of a practical system, substantial cost and fabrication advantages are achieved by using two types of corrugated membranes **20, 22** and two types of separator membranes **24, 24'**. The membranes **20, 22, 24** and **24'** provide the barriers and sealing necessary to control flow of the two fluids to and from the appropriate headers, while also maintaining the fluids separate. These basic elements are used in repetitive fashion to form a multilayer laminate of the size desired. An appreciation of the general arrangement of the membranes and the fluid flow paths, best shown in the exploded view of FIG. **3**, will assist in understanding the particular details of the individual membranes.

In FIG. **3**, the corrugated membranes **20** and **22** of first and second types respectively are shown as they are stacked in alternating fashion, with planar support membranes **24** and **24'** being interposed between each pair of corrugated membranes **20, 22**. The planar membranes **24, 24'** differ only in that one incorporates an aperture to be described below. When united in the final assembly, these various membranes successively abut in intimate layered contact. Inasmuch as the structure is equivalent at each end, only one end of the membranes has been illustrated in FIG. **3**. It will be evident that the side headers may be on the same or opposite sides, or interchanged with the end headers at one or both ends, at the option of the designer. It is clear also that any number of side headers could be placed along the longitudinal dimension of the heat exchanger, for purposes of injection or extraction of fluids at various process points. The corrugated membranes **20, 22** differ primarily in having substantially a mirror image relationship. In the following description terms such as "upper" and "under" are used for clarity of reference to the elements as viewed in the Figures, but it will be understood that the exchanger may be used in any attitude.

In FIG. **3**, in correspondence to FIG. **1**, the first gas is directed from the end of the assembly between the first and second corrugated membrances **20, 22** on each side of the interposed support membrane **24'**. More specifically, the first gas passes between the underside of the first corrugated membrane **20** and the upper side of the subjacent corrugated membrane **22**, as viewed in FIG. **3**. The second gas passes over the upper side of the first corrugated membrane **20** and below a superposed membrane **22** of the second type. This pattern of different gas flows between successive pairs of membranes **20, 22** or **22, 20** is repeated throughout the multilayer laminate. In each instance, the gas flows are on both sides of the interposed support membrane **24** or **24'**.

Between the underside of a first corrugated membrane **20** and the upper side of a second corrugated membrane **22** an open flow path exists at each end of the assembly. For the alternate corrugated membrane pairs, however, a side opening is defined by deviations along one longitudinal edge of the upper side of the first corrugated membrane **20** and corresponding edge on the underside of the second corrugated membrane **22** immediately above. The second gas flowing between these membranes is diverted transversely from the central interchange region **25** of the membrane, within a header transition region **26**. This header transition region **26** is approximately rectangular in area form in this example, and communicates with all of the longitudinal passageways in the interchange region **25**, as well as the side opening defined along the edges of the membranes **20, 22**.

Specific details of the configuration of a first corrrugated membrane **20** are shown in FIGS. **2** and **4**. Because each membrane within the interior of the stack has a median plane but has surface portions contacting the planar membranes that are immediately above and below, it is cconvenient to refer to upper and lower reference planes as well as the median plane in describing the various parts of the structure. The upper and lower nodes of the corrugations in the central interchange region **25**, for example, lie tangential to the upper reference plane and lower reference plane respectively. In the header transition region **26**, as best seen in FIG. **4**, the gases are free to flow transversely because the tops of the corrugations are in effect cut off, with the lower halves or valleys of the corrugations being interconnected by webs **28** lying in the median plane. Referring again to FIG. **3**, it will be appreciated that these facing mirror image surfaces of the second membrane **22** and the subjacent first membrane **20** define an internal volume constituting the header transition region.

A system of integrally formed peripheral seals prevents leakage to the exterior or between membranes. As shown in FIGS. **2** and **4**, one leg of a side channel **30** of U-shaped section is joined by a web **32** in the upper reference plane of the membrane **20** to the closest corrugation. A side peripheral lip **34** extends outward from the channel **30** to define the outer periphery of the membrane **20**. The base of the channel **30** and the peripheral lip **34** have substantial areal contact and seal to the corresponding surfaces of the lower and upper planar support membranes **24'** and **24**, respectively.

In the region of the side opening previously referred to, however, the peripheral lip **34** and side channel **30** include a generally U-shaped notch or depression **36** having a long base corresponding generally to the length of the header transition region **26**, the base lying in the median plane of the mmembrane **20**, coplanar with the webs **28**. This notch **36** and the facing notch in the supernosed membrane **22** of the second type, define the side opening **17** (FIG. **1**) communicating with the associated header. The depths of the notches **36** are very small relative to their length, being one-half the height of the corrugations.

Transverse end barriers closing off the longitudinal flow paths at the end of the membrane **20** are defined by an integral lip **38** in the upper reference plane. A corresponding lip **39** in the lower reference plane of the second type membrane **22** lies adjacent to the lip **38** across the end of the exchanger, so that the second gas can exit only through the side opening. The transverse end lips **38** merge into terminating end shoulders **40** which close off the corrugations.

As best seen in FIG. **3**, the planar membrane **34** between the first and second corrugated membranes **20, 22** has a coextensive area except for a generally rectangular opening about the header transition region. A generally U-shaped web **44** extends along one side and across the end of the membranes **20, 22**, to complete the seal between these membranes.

The flow path for the second gas, therefore, in the example of FIG. **4**, proceeds along the upper side of the membrane **20** within the interchange region **25** and into the header transition region **26**, the gas then being blocked from longitudinal flow by the transverse lips **38, 39** and flowing transversely across the median plane webs **28** toward the side opening whose bottom half is defined by the U-shaped notch **36** in the side peripheral lip **34.** At the same time, there is a parallel and adjacent flow of the second gas along the underside of the superposed second corrugated membrane **22,** toward the same side opening.

It will be appreciated that the gases flowing in the corrugation passageways below the median plane of the membrane **20** are diverted upwardly at the header transition region **26** in moving transversely to pass between the median plane and the upper reference plane. No significant pressure drop results, however, because there is substantially the same cross-sectional flow area due to the absence of the upper part of the corrugation.

The first gas enters under the first membrane **20** and across the top of the next lower second membrane **22** by passing between the transverse end lips **38, 39.** The first gas, moving in counter-current relation to the second gas, moves between but on the opposite sides of the header transition regions **26.** The first gas does encounter a restricted cross-sectional flow area in this region. The restriction, however, is found in practice not to introduce a significantly discernible pressure drop.

With this arrangment, the first and second gases are maintained completely separate from each other. For the flow of second gas between a first membrane **20** and the superposed second membrane **22,** the abutting peripheral side lips **34** and the interposed planar membranes **24** are open only at the notches **36** defining the side opening **17** (FIGS. **1** and **2**). The first gas does not communicate with any side openings in passing between a second membrane **22** and the superposed first membrane **20,** but passes through the end apertures **14.** The physically displaced side and end openings **14, 17** may be conveniently coupled into any desired header or conduit system.

Apart from the mirror image relationship, the primary distinction, referring now again to FIG. **2,** between the first and second corrugated membranes **20, 22** is that the web portion **32** in the second corrugated membrane **22** is longer by the width of one corrugation, in order to maintain the desired precisely in-phase relationship between the corrugations. From the structural standpoint both membranes **20, 22** are essentially the same. The sinuous corrugations substantially stiffen the thin membranes, and eliminate unsupported lengths of material. All abutting surfaces of the membranes and the adjacent planar membranes **24, 24'** are bonded together for superior physical integrity, but this is not needed in all applications.

Processes of fabricating corrugated membranes and assemblies in accordance with the invention utilize vacuum and pressure forming of the corrugated membranes against a mold in controlled heating and cooling cycles. Although the plastic material is desirably thin, it is important for strength, freedom from defects and effectiveness to achieve sinuosity which approaches a rectangular wave configuration without having substantial variations in wall thickness. Such results are achieved by both vacuum and pressure forming a sheet with precise temperature control through a slow heating cycle, and then using a relatively slow cooling cycle to return the part to ambient temperature. The sheets are formed with excess material around the edges, and receive strips **11** of heat conductive material, preferably by vacuum deposition of a thin (e.g., 0.0005 inches) prior to forming. Subunits of the assembly, comprising a corrugated membrane and a planar membrane are first assembled, by spraying the planar membrane with an adhesive dissolved in solvent and pressing the parts together, while maintaining the corrugated membrane in a matched mold. Through these steps, the membranes are maintained in precise positional relationship by alignment with positioning pins inserted in positioning holes punched in the excess trim portion. Then, after the excess material around the headers is trimmed, the subunits are built up into a complete assembly, by successive steps of adhesive bonding under pressure as previously described. Thereafter, when the assembly is built up to a desired number of layers to provide a chosen cross-sectional area for flow, the excess material beyond the peripheral lip portions is trimmed off and the side and end apertures are coupled to associated manifolds or headers.

A completed assembly therefore appears as in the fragmentary view of FIG. **5,** with the end openings **14** being alternated in the successive layers with the side openings **17.** Within the laminates, the corrugations appear in cross-section essentially as shown in FIG. **6,** which is greatly enlarged in scale but corresponds closely to the actual relationships and shapes involved. It should be noted that the thickness of the corrguated membrane **30** does not vary substantially at the top, bottom or sides, so that pin hole defects or ruptures of the material do not occur. In addition, the bonding material **48** adheres between the corrugated membrane **20** and the planar membranes **24** and **24'** and enhances the rectangularity of the corrugations when bonded and cured under small pressure. The result is to augment the checkerboard effect and increase the interchange area ratio to the volume of fluid.

The achievement of a checkerboard pattern, with minute passageways, enables the system to take advantage of certain fundamental considerations of heat transfer, and to be able to achieve high efficiency. The thermal gradient within the fluid in a passageway is dependent upon the effective radius of the passageway from its center. The thermal gradient within a fluid varies in accordance with the radius, and consequently with either adequately uniform flow distribution or lateral temperature integration, property interchange within a passageway can be the predominant limitation of effectiveness. By reducing the size of the passageways and facilitating transfer from a given passageway directly through thin membranes in virtually all directions, optimum heat transfer conditions are achieved. The dependence of effectiveness of transfer upon smallness of passageway size is developed in detail at page 237 of the book *Heat Transmission*, McGraw-Hill Series in Chemical Engineering, Mc-Graw-Hill, New York, 1954, 3rd Edition.

It will be appreciated that although the system of FIGS. **1** to **6** has been described in terms of a heat exchanger for operating in a given temperature range, the same conditions apply to other ranges, up to a level at which thermal degradation of the materials involved becomes of concern. Additionally, the property interchange function directly relates to a number of other applications, such as dialysis, ion exchange and oxygenation functions. In the handling of blood, for example, it is highly desirable to avoid substantial pressure gradients, turbulent flow and abrupt discontinuities. It is also highly desirable to achieve effective purification in a dialysis unit by the use of counter-current flow with a high interchange area per unit of volume. All of these conditions are achieved by structures in accordance with the present invention.

FIGS. 7 and 8 illustrate the general organization and particular details of another heat exchanger system having high efficiency and extreme compactness but also using elements that can be readily fabricated and easily assembled.

As best seen in FIG. 8, which is a greatly enlarged view of a segment of the heat exchanger, in which relative dimensions are not to scale in order to show the elements more clearly, the basic heat exchanger elements comprise thin corrugated membranes **110**, with the corrugations running parallel and lengthwise along the membrane. Of the order of fifty corrugations per inch may be employed for use in the present system, and the peak-to-valley dimension may be of the order of approximately **30** mils, with a membrane of the order of 0.002 inches in thickness. The membrane **110** itself is preferably of a thermosetting plastic of one of the types conveniently used in thermoforming such as the material sold under the trademark "LEXAN." The corrugated configuration can be achieved by shaping the plastic between dies after bringing it above the plastic flow temperature. The waviness or repetitive deviation of the membrane **110** from its median plane to define gas passageways need not follow the generally sinusoidal form that is associated with the term "corrugation." Instead, the membrane **110** may deviate to define grooves, or peaks and valleys, in any desired periodic or even aperiodic fashion.

For separation of the gases, and for headering purposes, the peaks and valleys on opposite sides of the membrane **110** are affixed respectively to an intermediate thin lamination **112** and a relatively thicker spacer **114**. As may be seen in both FIGS. 7 and 8, the intermediate laminations are disposed between a pair of membranes **110**, and run the full length of the heat exchange structure. The spacers **114**, however, are discontinuous along the length of the heat exchanger, and the spacers **114** and intervening open volumes are utilized for several purposes.

It is convenient for purposes of illustration and description to regard the laminated structure comprising a pair of membranes **110** between a pair of thicker spacers **114** as a heat exchanger entity. This entity is then bounded by the thicker spacers **114**, and includes an adjacent and coextensive pair of membranes **110** between which the intermediate thin lamination **112** is interposed for the full length of the heat exchanger. The laminations **112** and the spacer **114**, may as with the membranes **110**, be of a suitable plastic material. Regarding the thin lamination **112** as the center of the structure, the interior adjacent passageways whose sides are bounded by the lamination **112** and the two adjacent membranes **110** provide flow paths from one end of the heat exchanger to the other. What may be termed the exterior passageways within the entity are the passageways defined between the opposite sides of the membranes **110** and the outer spacers **114**. A first gas or mixture passing in one direction along the length of the heat exchanger within the interior passageways is therefore completely separated from a second gas or mixture passing along the exterior passageways. If leakage occurs due to improper bonding between the membrane and the intermediate lamination **112**, there is neither a substantial temperature differential between the gases nor a mixing of unlike gases. The open volumes between the separate thicker spacers **114** provide access to all of the exterior passageways of an entity from a side of the heat exchanger. These outer open volumes communicate with the outer passageways on the lower side (as seen in FIG. 7) of the upper entity, and the upper side of the next lower heat exchanger entity. All of these open volumes communicate with common side manifolds or headers positioned at two or more regions along the heat exchanger. The necessary separation between the gas mixtures is provided by sealing surfaces **120** closing off the exterior passageways at the ends of the system, and by sealing membranes **121** closing off the interior passageways at the side header regions.

As shown in both FIGS. 7 and 8, therefore, gases in the interior passageways moving in a first direction (from right to left in FIGS. 7 and 8) pass from one end header **116** to the opposite header **118**. The second gas mixture passing in the opposite flow direction is fed from one side header **122** through the heat exchanger, to the opposite side header **124**.

The greatly simplified and idealized representation of FIG. 7 therefore shows a complete heat exchange structure **92** built up of successive laminations of the basic heat exchange entities until the desired cross-sectional areas for flow of the two gas mixtures are attained. It will be appreciated that the continued lamination of additional elements does not in any way change or further complicate the headering arrangement and that many hundreds of entities may be utilized. In a practical example, a heat exchanger having external dimensions of approximately 2.4 inches by 4 inches by 1.5 feet provides the needed heat transfer capacity for an individual life support system. This system operates between the breathable temperature range and the cryogenic range at approximately 80°K, transferring approximately 100 BTU per minute with better than 99 percent temperature exchange efficiency, and with a total heat exchanger volume of the order of 0.1 cubic foot. The gas passageways are linear, and as noted, a substantial cross sectional area is made available for gas flow, together with an extremely large heat transfer area. Thus, a low pressure differential (less than approximately 1 inch - H_2O) exists within the system. This arrangement is further characterized by the fact that standardized heat exchange sections may be assembled of selected length and cross sectional areas. For greater capacity or efficiency, these may be series or parallel connected simply by appropriate interconnection between the heat exchange headers.

The heat exchanger structure is also arranged to provide an additional heat transfer function, extracting heat from the principal countercurrent gases with high efficiency. It will be appreciated that a temperature drop or rise may be augmented simply by insertion of an available high or low temperature source in close contact with the heat transfer entities, in view of the unrestricted interior volumes between the entities and headers. Apart from this obvious expedient, however, it is desirable in the present example to provide heat extraction from the counter-flowing gas mixtures without substantially impeding gas flow and by utilizing a substantial heat exchange area. To this end, low temperature gases from a boil-off manifold **125** are passed through a tortuous conduit **126** interposed between the facing sets of exterior passageways in adjacent heat exchanger entities, and between the side headers **122, 124.** The gases in the exterior passageways are kept separated by thin interior laminations **127.** A tertiary heat exchange is thus effected, utilizing the boil-off gases as a heat sink that acts substantially upon both counter-flowing gases through that gas flowing in the second direction within the heat exchanger, between the side headers **122, 124.**

FIGS. **9–11** illustrate a different exchanger **50,** arranged to provide what may be termed in-line or end headering. As in the example of FIG. **1,** the exchanger **50** comprises a multilayer laminate of first and second, substantially mirror image, corrugated membranes **52, 54** and interposed first and second planar membranes **56, 58.** As in the example of FIGS. **1–6** the membranes **52, 54, 56, 58** are disposed in a repetitive pattern, and first and second gases are passed between alternate pairs of corrugated membranes in opposite longitudinal directions. Again, the corrugated membranes **52, 54** have substantially mirror image configurations. Also, as in the previous example, the extreme upper and lower nodes of the corrugations of membrane **52** are tangent to upper and lower reference planes, respectively.

Each corrugated membrane **52** or **54,** however, includes, adjacent each longitudinal end, a pair of header transition regions, these being formed integral with the membrane itself, separated longitudinally, and associated with header transition volumes on opposite sides of the membrane. Each transition volume, defined at a particular longitudinal region between the facing membrane surfaces, provides at least partially transverse gas flow, and is in communication with a different end header.

Referring now to FIGS. **10** and **11** particularly, only the disposition of first and second header transition regions **60, 62** on the first corrugated membrane **52** need be discussed in detail. As indicated, the first and second gas flows are respectively under and over (as viewed in FIG. **10**) the membrane **52.** The first header transition region **60** is closest to the longitudinal end of the membrane **52** and is defined by bottom-half corrugation segments **64** interconnected by median plane webs **66.** Thus the upper half of the membrane **52** volume is open for partially transverse flow of the second gas in this region. The second header transition region **62** is defined by upper-half corrugation segments **68** joined by median plane webs **70,** permitting at least partially transverse flow of the first gas.

Other elements and relationships are also used in achieving the desired flows. The side lips **72** and side channels **74** run the full length of the membrane **52.** Along the transverse edge, however, a first edge sealing lip **76** of approximately half the membrane **52** width and lying in the lower reference plane is coupled to a second edge sealing lip **78** lying in the upper reference plane by a perpendicular central wall **80.** Another feature is that the first gas, passing along the underside, is closed off from the first edge sealing lip **76** by terminating shoulders **82** in the adjacent half-height corrugation, defined by the webs **66.** In like fashion, shoulders **84** terminate the corrugations in the other transverse half of the membrane **52,** adjacent the second edge sealing lip **78.**

The second type membranes **54** which are immediately above and below the first membrane **52** thus together with the interposed planar membranes **56, 58** define side-by-side sets of apertures separated down the center of the exchanger **50** as best seen in FIG. **9.** Each set communicates with a different header or other conduit (not shown). The planar membranes **56, 58** include principal apertures **86, 88** respectively which encompass the associated header transition region of the membranes, and also are open to the appropriate end aperture.

Consequently, the second gas, in flowing from the interchange region to the appropriate exchanger **50** outlet, first passes across and over the second header transition region **62.** Upon entering the open volume of the first header transition region **60,** gas flowing on the right side (as viewed in FIG. **10**), is blocked from the end by the shoulders **84** and the second edge sealing lip **78.** This gas flow is then directed transversely across the first header transition region **60** and out between the side lip **72** and the center wall **80.** The first gas, moving under the membrane **52** at the second edge sealing lip **78,** passes along beneath the second header transition region **60** until reaching the second header transition region **62.** At this region the first gas is distributed least partially transversely across all the passageways.

For a full in-line system, like header conduits and header transition regions are used at each end of the exchanger. It will be apparent to those skilled in the art, however, that a wide range of alternative configurations are available through the use of two or more header transition regions. For example, end configurations including two side headers or one side and one in line header are possible. The flexibility provided by the invention with respect to header configurations is not limited to end regions. Side headers, communicating with their own header transition regions, may be disposed at any point along the length of the exchanger. Fluid injection and expulsion may consequently be carried on throughout the extent of the exchanger in accordance, for example, with the requirements of a chemical process occurring within the system. The invention clearly is not limited to situations in which fluids enter at one end and exit at the other.

Headers may be arranged so as to communicate with header transition regions and passageway sets in any desired pattern. With a proper choice of passageway sets, patterns of fluid flow can be set up to allow fluids greater than two in number to be in exchange relationship with one another. In a three fluid model, for example, a fluid such as blood could exchange properties with two other fluids which for physical or chemical reasons could not be mixed together for property exchange with the blood. The headers communicating with the passageways through which the blood flows may be similar to those discussed above. The headers for the other two fluids may be arranged so as to inject each of the fluids in alternate layers of the exchanger. The resulting pattern of fluid flow then may provide for each blood flow being surrounded by two sets of passageways, each set containing one of the other two fluids.

Means of equalizing the temperature states of different flow lines, which may be used with any of the previously discussed forsm of the system, are illustrated in FIGs. **9** and **12.** Referring to FIG. **9,** a slot **89** extends across the width of the planar membrane **58** in a region in the exchange region of the exchanger **50.** Separate passageways in a thin sheet-like passage defined by the corrugations of membranes **52** and planar membrane **58** are brought into communication by slot **89** as are passageways in a passage defined by the corrugated membrane **54** in the planar membrane **58** in the layer above. Both these passages contain flows of the second gas. Interpassage communication between layers is also provided by slot **89.** Thus, three-dimensional physical mixing of previously separated flows of the second gas is provided by slot **89.** After mixing, the gas then resumes its normal longitudinal flow.

FIG. **12** shows a fragment of heat exchanger which comprises first and second mirror image corrugated membranes **90, 94** stacked alternately with first and second planar membranes **96, 100.** A first gas flows in a passage containing separate passageways defined by corrugated membrane **94** and planar membrane **96** and in separate passageways in a passage under member **90** defined by membrane **90** and planar membrane **96**; a second gas flows under membrane **94** and over membrane **90** in passageways of passages defined in a similar manner with planar membrane **98.** Only situations involving the first gas need be discussed.

An internal communication volume is formed by facing mirror image internal header regions **100, 106** similar to the header transition region of FIG. **4.** Unlike the FIG. **4** header region there are no side openings here, longitudinal edges **102, 104** of the corrugated membranes **94, 90** being in the same plane as their continuations ouside this region. Also unlike the situation of FIG. **4,** there is no transverse barrier to flow at ends of the internal header regions, gas flow being longitudinal at each end of the internal header regions.

The internal communication volume comprises an internal header permitting communication among the passageways of the first gas passages. A slot **108** in planar membrane **96** extending across the width of the membrane and longitudinally for the extent of the internal communication volume permits communication between the first gas passages. Thus, the first gas enters the internal communication volume in spearate flow within separate passages and experiences interpassageway mixing within each passage due to the internal header regions **100, 106.** The gas flows within each passage intermix through the slot **108.** The means of physical mixing of gas flows illustrated in FIGS. **9** and **12,** internal headers and slots, may be used separately or in combination, as shown.

Physical mixing achieved in the embodiments of FIGS. **9** and **12** makes uniform the temperature of the gases within the regions of mixing thus minimizing the effect of any temperature differences between flows in different passageways and passages due to small deviations in flow arising from variations in passageway size or other causes.

Temperature equalization may also be achieved by inducing turbulence in the gas flows, for example, by means of roughening passageway interiors or introducing obstacles to straight flow. Turbulence may also be used separately or in combination with the means illustrated in FIGS. **9** and **12.**

Although a number of alternative forms and modifications of systems in accordance with the invention have been described, it will be appreciated that the invention is not limited thereto, but encompasses all variations and modifications falling within the scope of the appended claims.

What is claimed is:

1. A property interchange system for fluids comprising:

a plurality of corrugated membranes of a material of low conductivity with respect to said property having corrugations lying substantially parallel to a selected longitudinal axis, said membranes being stacked coextensively to define a multilayer laminate body, the corrugations being in-phase relation and the interior space between each successive pair of membranes defining fluid passages substantially separated by said corrugations into separate longitudinal passageways;

first header means communicating with first fluid passage sets between first selected pairs of membranes to pass a first fluid therealong;

second header means communicating with second fluid passage sets between second selected pairs of membranes to pass a second fluid therealong in countercurrent relationship to the first fluid, said first and second selected pairs of membranes alternating across the height of the laminate body, such that different fluids pass on opposite sides of each membrane and property transfer takes place through each membrane;

the corrugations of said membranes having a height to width ratio of approximately one, there being in excess of approximately 20 corrugations per inch and each passageway thereby being substantially encompassed by passageways for the other fluid; means laterally disposed relative to the longitudinal axis along said membranes for equalizing the property state of at least one of said fluids at least one region along said longitudinal axis.

2. A heat exchanger comprising:

a substantially rectangular body including a plurality of thin laminate membranes of low heat conductivity, said membranes having corrugations whose length lies parallel to a selected axis of the body, the broad faces of adjacent pairs of membranes defining substantially distinct sheet-like passages along the selected axis, the corrugations thereof providing an extended surface area and dividing the passages into substantially distinct passageways;

means feeding different ones of a pair of fluids alternately into the passages between adjacent membrane pairs, such that heat transfer between fluids takes place directly through the membranes; and,

wherein there are at least about 250 passageways per square inch in cross-section of said body,

wherein said membrane thicknesses are no greater than approximately 0.005 inch, and wherein the corrugations are periodic and similar within the corrugated membranes, and disposed in an in-phase relationship between adjacent membranes such that heat exchange between the fluid in a passageway and gas of the other type in adjacent passageways takes place in three dimensional and omni-directional fashion directly through the membranes,

wherein said exchanger further includes a plurality of planar support membranes interposed between each pair of corrugated membranes, and having thickness of no greater than approximately 0.020 inch,

wherein at least the central portions of said membranes are corrugated, the corrugated membranes are of thermo-formed polycarbonate resin material having corrugations of generally sinusoidal form, in which the height-to-width relationship of the corrugations average no less than approximately 1:1, wherein in addition means disposed between said corrugated membranes adhesively join abutting surfaces of adjacent support and corrugated membranes, wherein the corrugated membranes include transverse and longitudinal edge sealing members disposed in substantially mirror image relationship and joined together in selected patterns, lateral temperature equalization means comprising a plurality of thin conductive strips, each disposed within a different passage at a longitudinally spaced region therealong and conducting heat between the passageways of the passage to equalize the temperature in such passageways at said longitudinally spaced region, and wherein the heat exchanger operates from the near cryogenic temperature range to an approximately ambient temperature range.

3. A property interchange system for fluids comprising a substantially rectangular body including a plurality of thin membranes including central corrugated regions whose length lies parallel to a selected axis of the body, the broad faces of adjacent pairs of membranes defining a set of substantially distinct passages along the selected axis, means feeding different ones of a pair of fluids along opposite sides of the individual membranes, such that transfer of properties takes place directly through the membranes, and wherein said corrugations divide said passages into at least about 1000 passageways per square inch in cross-section of said body, the passageways for each fluid being directly aligned throughout the height of said body with the superposed passageways for the opposite fluid such that an approximate checkerboard distribution of passageways is achieved.

4. A property exchanger comprising a central matrix of passageways for fluids whose properties are to be interchanged, said matrix being defined by a plurality of layers of corrugated membranes, the corrugations having a height-to-width ratio of about 1:1, the membranes being less than about 0.005 inches thick and of thermoformable plastic material, there being approximately 50 corrugations per inch, and the corrugations in successive layers being in in-phase relation;

means for feeding fluids whose properties are to be interchanged into alternate adjacent passageways in countercurrent relationship, such that a checkerboard fluid flow pattern is established in the respective passageways throughout the matrix.

5. The invention as set forth in claim **4** above, wherein said corrugated membranes have relatively low thermal conductivity and wherein, in addition, planar support membranes are disposed between said corrugated membranes, said planar support membranes being less than approximately 0.020 inches thick, and wherein bonding means couple the opposite extremities of the ridges and grooves of the corrugations to said planar support membranes.

6. The invention as set forth in claim **5** above, wherein said property exchanger is of rectangular form, wherein said first and second corrugated membranes have coextensive rectangular outlines, and wherein said means for feeding fluids comprises extended interlayer openings having heights substantially equal to the corrugation heights.

7. The invention as set forth in claim **6** above, wherein selected pairs of said corrugated membranes include integral header transition regions in communication with selected ones of the inter-layer openings.

8. The invention as set forth in claim **7** above, wherein the different apertures comprise spaced apart side and end apertures.

9. The invention as set forth in claim **7** above, wherein said exchanger also includes planar support sheets between adjacent pairs of membranes, and wherein said membranes also include integral longitudinal edge sealing members, defining side apertures between selected pairs of membranes, and integral transverse edge sealing members defining end apertures between other selected pairs of membranes.

10. A heat exchanger comprising:

a plurality of thermoformed sheets of first and second types;

a plurality of support sheets;

said thermoformed sheets and support sheets being stacked in multilayer laminate relation, said thermoformed sheets being alternated between said first and second types, said support sheets being interposed between each adjacent pair of thermoformed sheets, all said sheets being substantially coextensive and rectangular in plan;

said thermoformed sheets each having a central corrugated region with corrugations running lengthwise, said corrugations having selected heights and depths from the median plane of the sheet, such that the heights and depths lie tangential to first and second reference planes respectively, said sheets also each including terminal header transition areas adjacent each end thereof and comprising half-corrugation segments and planar webs disposed approximately in the median plane joining said half-corrugation segments, said thermoformed sheets also including integral side and end sealing surfaces, said side sealing surfaces comprising a longitudinal side lip and an adjacent channel, and said end sealing surfaces comprising a transverse end lip and terminating shoulders in said corrugations, said side sealing surfaces further including shaped aperture-defining surfaces in communication with the interior header transition regions, the corrugations in the sheets of the first and second types having like periodicity and being directly in phase;

first inlet and outlet header means communicating with said transition regions;

second inlet and outlet header means communicating with the lengthwise ends of the laminate.

11. The invention as set forth in claim **10** above, wherein said support sheets comprise planar membranes, and both said thermoformed and said support sheets are of thin plastic material of relatively low heat conductivity, wherein said first and second types of thermoformed sheets have substantially mirror image configurations with the web portions of said header transition regions in adjacent ones of each thermoformed sheets being in facing relation, wherein aperture-defining surfaces of said side sealing surfaces are between first alternate pairs of said thermoformed sheets, to provide a first set of apertures along the side of said exchanger, and wherein the end sealing surfaces seal the ends of said first alternate pairs and are open between the remaining alternate pairs of said thermoformed sheets, to provide a second set of apertures along the end of said exchanger, and spaced apart from said first set of apertures.

12. A heat exchanger for operation between the near cryogenic range and an ambient temperature range comprising:

a plurality of thermoformed sheets of first and second types having substantially mirror image relationships, said thermoformed sheets each having a central corrugated region with corrugations running lengthwise relative to the longitudinal exchanger axis, said corrugations varying from the median plane of the sheet in generally sinusoidal fashion to define ridge nodes tangential to an upper reference plane and groove nodes tangential to a lower reference plane, said upper and lower reference planes and the sinusoidal variations of said corrugations providing a height-to-width ratio for said corrugations of approximately 1:1, there being in excess of approximately 50 corrugations per inch, and said thermoformed sheets being of approximately 0.001 inch in thickness and of polycarbonate resin material, said sheets also each including header transition regions in the form of a corrugated area comprising unidirectionally varying half-corrugation segments and planar webs joining said half-corrugation segments at approximately the median plane, said thermoformed sheets also including peripheral sealing means extending thereabout and including side channel means having a base lying in one of the reference planes, and a side peripheral lip lying in the other of the reference planes, said side channel means and side peripheral lip including a generally U-shaped notch having an extended base lying approximately in the median plane adjacent to and communicating with the different header transition regions, said sheets further including edge peripheral lips at each lengthwise end transverse to the longitudinal axis, said edge peripheral lips lying in one of said reference planes, said sheets of first and second types being substantially coextensive and rectangular in plan;

a plurality of planar support sheets of thin plastic material coextensive with said thermoformed sheets, and including areal apertures adjacent each end corresponding to the outline of the header transition regions and including an opening corresponding to the U-shaped notch portions;

said thermoformed sheets and said planar support sheets being stacked in multilayer laminate relation, said thermoformed sheets being alternated between said first and second types, with the U-shaped notch portions facing to define the peripheries of side apertures communicating with interior header transition volumes defined by facing header transition regions, said support sheets being interposed between each adjacent pair of thermoformed sheets, with the side openings therein corresponding to the side apertures defined by said U-shaped notch portions;

adhesive means disposed between said thermoformed sheets and said support sheets and bonding corrugation nodes of said thermoformed sheets to the facing adjacent support sheet along the length of the corrugations;

first inlet and outlet header means disposed along the sides of said heat exchanger, and each communicating with the side openings defined by the exchanger;

and second inlet and outlet header means disposed adjacent to the longitudinal ends of the exchanger and each communicating with the set of side apertures between adjacent alternate pairs of thermoformed sheets within the exchanger at the corresponding end of the exchanger.

13. The invention as set forth in claim **12** above, wherein one type of thermoformed sheet includes at least one additional corrugation therein relative to the other type of thermoformed sheet, wherein the corrugations in said thermoformed sheets are disposed in inphase relation, and wherein said thermoformed sheets and bonding means have substantially like thermal coefficients of expansion.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,847,211 Dated November 12, 1974

Inventor(s) Halbert Fischel and Anthony Dichiro

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 1, line 15, "otherwide" read --otherwise--; line 33, the formula read:

$$T.E.E. = 1-\frac{\delta T}{\Delta T} \text{ where } \delta T =$$

Column 2, line 54, "mmem-" read --mem- --. Column 3, line 62, "cpmbinations" read --combinations--. Column 4, line 25, "end" read --ends--; line 44, "Diifferent" read --Different--. Column 6, line 19; "realtionship" read --relationship--; line 52, "corrguated" read --corrugated--. Column 8, line 28, "suffficiently" read --sufficiently--; line 62, "elemments" read --elements--. Column 9, line 63, "area" read --areal--. Column 10, line 1, "corrru-" read --corru- --; line 6, "cconvenient" read --convenient--; line 38, "mmembrane" read --membrane--; line 40, "supernosed" read --superposed--. Column 11, line 25, "arrangment" read --arrangement--. Column 12, line 26, "corrguated" read --corrugated--. Column 15, line 61, "tion" read --tions--. Column 16, line 63, "forsm" read --forms--. Column 17, line 11, after "of" and before "heat" insert --a--; line 40, "spearate" read --separate--.

Column 18, line 64, "thickness" read --thicknesses". Column 19, line 65, "comprises" read --comprise--.

Signed and sealed this 13th day of May 1975.

(SEAL)
Attest:

RUTH C. MASON
Attesting Officer

C. MARSHALL DANN
Commissioner of Patents
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