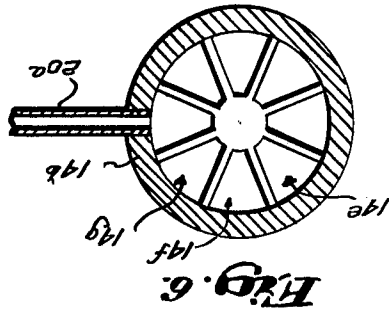
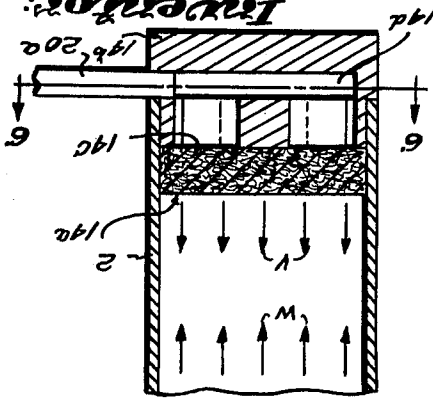
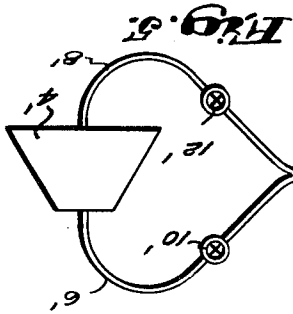
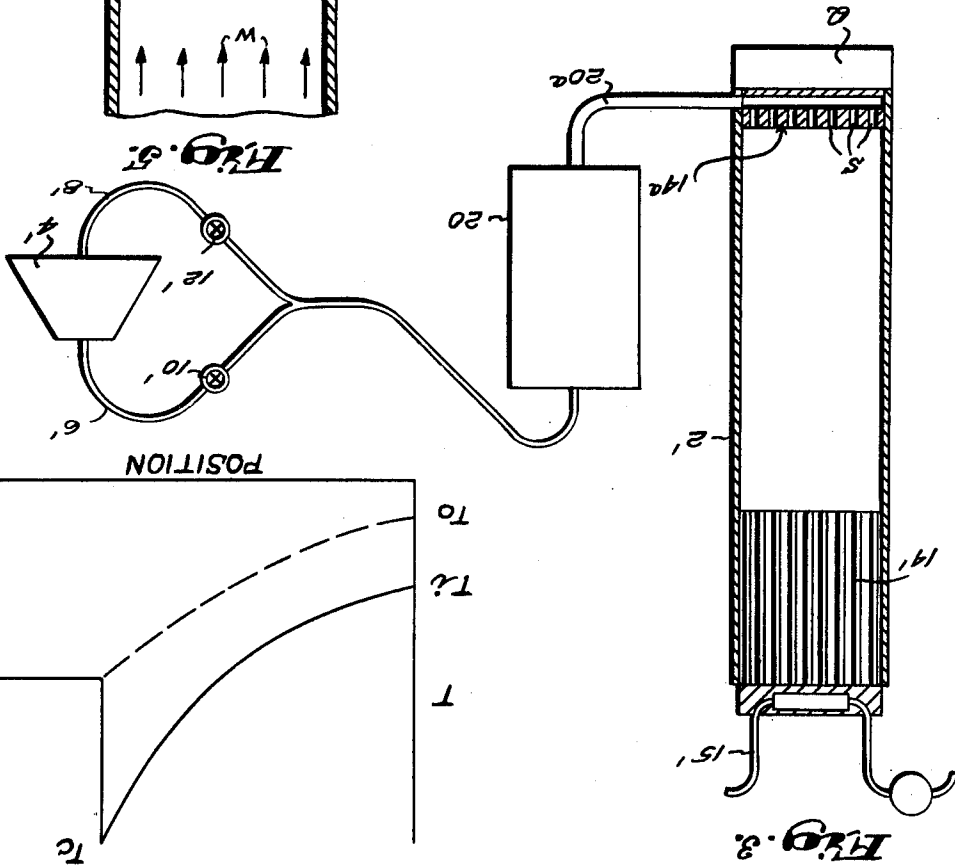
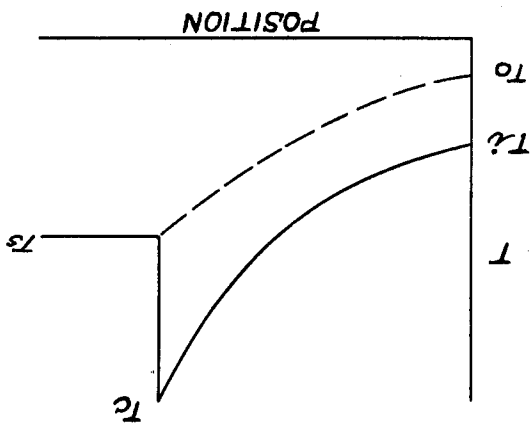
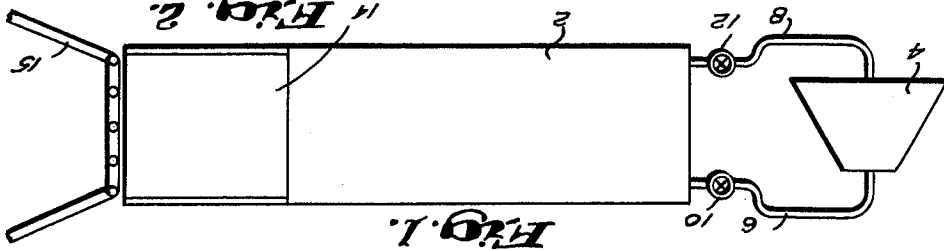




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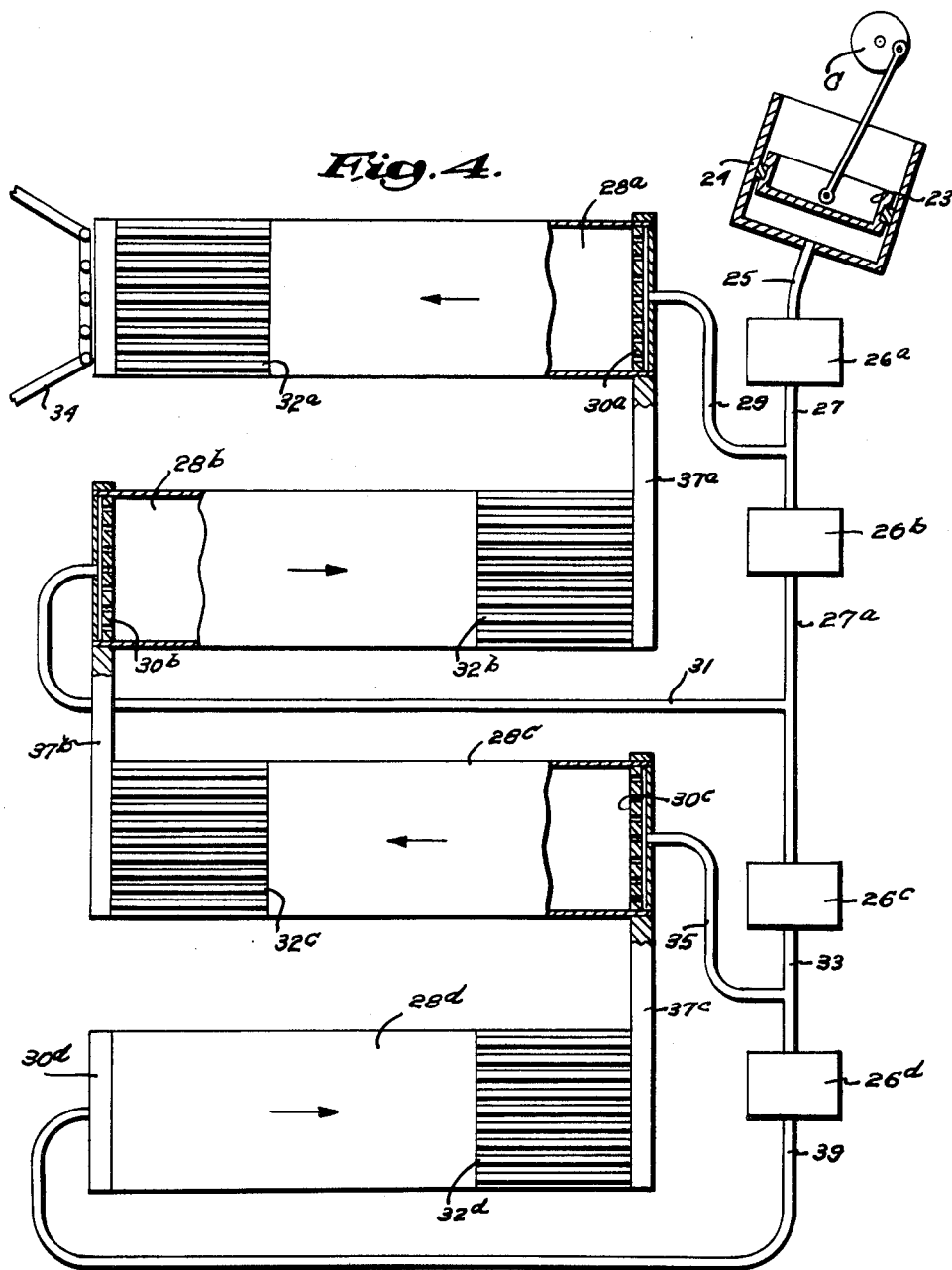
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PULSE TUBE METHOD OF REFRIGERATION AND APPARATUS THEREFOR

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2 Sheets-Sheet 2



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PULSE TUBE METHOD OF REFRIGERATION AND APPARATUS THEREFOR

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13 Claims. (Cl. 62—88)

The present invention is a continuation-in-part of application Serial No. 279,379, filed May 10, 1963, now abandoned.

This invention relates to an improved method and apparatus for producing refrigeration and, more particularly, to a method of laminar flow cooling in which very low temperature refrigeration is achieved by means of an oscillating pressure exerted in a gas filled tubular enclosure. The pressurized volume of gas is controlled so as to move in and out of the tubular enclosure with lamina flow parallel to the axis of the tubular enclosure and there is thus set up a novel heat exchange mechanism, whereby a significant temperature gradient may be continuously induced in the tubular enclosure.

The method of the invention is hereinafter referred to as "Pulse Tube Refrigeration" and the apparatus is referred to as a "Pulse Tube Refrigerator." The invention has for its principal objective the originating of a new concept of cooling and the embodying of this concept in one or more practical working forms whereby useful refrigeration in a range of very low temperatures may be realized.

Another object of the invention is to provide an improved method of refrigeration which utilizes an apparatus having a minimum number of moving parts capable of achieving relatively low temperatures without being subject to problems relating to wear, faulty sealing, valve failure, and the like.

Another objective is to devise an apparatus of the character described which is of relatively high efficiency which is capable of being carried on in multi-stages so that progressively induced cooling may be accomplished to realize refrigeration at very low temperatures with relatively inexpensive equipment.

The nature of the invention and its other objects and novel features will be more fully understood and appreciated from the following description of preferred embodiments of the invention selected for purposes of illustration and shown in the accompanying drawings, in which:

FIGURE 1 is a diagrammatic view of one simple form of pulse tube apparatus by means of which a gas may be compressed, heated, and then expanded with a net cooling taking place and a continuous temperature gradient being induced;

FIGURE 2 is a diagrammatic view in graph form showing the changes the gas undergoes in order to achieve refrigeration at temperatures lower than room temperature;

FIGURE 3 is a diagrammatic view of another form of pulse tube of the invention in which portions of the pulse tube is shown in cross section;

FIGURE 4 is a modified form of apparatus of the invention including multi-stage pulse tube cooling units by means of which progressively lower temperature may be achieved;

FIGURE 5 is a fragmentary cross sectional view of a pulse tube and heat exchanger construction; and

FIGURE 6 is a detail cross sectional view taken approximately on the line 6—6 of FIGURE 5.

The method of pulse tube refrigeration of the invention is, in general, based upon the concept of a novel heat exchange mechanism which operates to provide both a cooling effect in a first part of a confined space and a heating effect in a second part of said confined space in

such a manner that heat is pumped from the first part to the second part.

In accordance with the invention method, oscillating pressure is exerted on a gas confined in a tubular enclosure and the pressurized volume of gas is caused to move in and out of the tubular enclosure in a laminar flow pattern parallel to the axis of the tubular enclosure. The cooling effect noted above is accomplished at one end of the tubular enclosure and the heating effect noted above takes place at the opposite end of the tubular enclosure. As a result of these two effects a significant temperature gradient may be continuously induced in the tubular enclosure where heat is being pumped from the cold end to the hot end.

The method of the invention in one simple form is illustrated diagrammatically in FIGURE 1. As shown therein an enclosed volume 2 is connected to a source of compressed air or other gas from a compressor 4 by conduits 6 and 8 which are fitted with suitable valve means 10 and 12. A heat exchanger 14 is located at one end of volume 2 and is maintained by suitable cooling means 15 at a constant temperature as room temperature. It should be understood that there may be employed another heat exchanger in the entrance end of the tubular enclosure 2.

In operation, gas under pressure from the source 4 is supplied through valve 10, while valve 12 is closed for a short interval (a second or less) in which the gas volume in the enclosure 2 is compressed and heated. Heat of the compressed volume of gas at the further end of the volume 2 is transferred to the heat exchanger 14. Any gas may be used in the refrigeration method which remains a gas throughout the temperature and pressure range of the desired cooling operation. For example, air can be used down to 120° K.; hydrogen can be used down to 30° K., and helium can be used down to 6—8° K.

Immediately thereafter the gas from which heat is removed is returned by closing valve 10 and opening valve 12. This allows gas returning from the heat exchanger to expand and as this occurs the portion of gas thus expanded tends to cool to a lower temperature than it was at when it entered the valve 10. Thus it will be apparent that when heat is removed from the heat exchanger 14, by cooling means 15, it becomes feasible to exhaust gas at a temperature lower than the temperature of the gas as it enters volume 2.

This illustrated diagrammatically in FIGURE 2 wherein T_i indicates temperature of a portion of gas as it enters volume 2; T_c is the temperature of a compressed portion of the gas; T_s is the temperature of the gas after giving up heat to the heat exchanger 14; and T_o is temperature of gas after it returns and becomes expanded.

In order to produce refrigeration more efficiently and at much lower temperature than that possible with the device of FIGURE 1, I may employ a further arrangement of this general nature as shown, for example, in FIGURE 3 wherein I have indicated an enclosed volume 2' in which is provided a heat exchanger 14' and also a second flow smoothing heat exchanger 14a. Gas is furnished from a compressor 4' through conduits 6' and 8' controlled by volumes 10' and 12' and also through a regenerator 20. Gas is conducted from the regenerator 20 through conduit 20a to the lower side of heat exchanger 14a.

The heat exchanger 14' is located in the confined end of enclosed volume 2' and may be of a conventional type and operates in the usual manner. The flow smoothing heat exchanger 14a is located at the entrance end and performs two functions. It gives up heat to the exhausting gas and becomes cooled, and it causes all the gas to move in the tube with laminar flow parallel to the axis of the tube. Some portions of the gas move

different distances than other portions in the tube but in parallel paths of travel without turbulent mixing with one another.

I have determined that pulsing movement of the gas in the manner described above may, for example, be accomplished by travelling portions of the gas through a flow smoothing heat exchanger having a multiplicity of substantially uniformly sized passages each of which is characterized by substantially equivalent functional flow resistance.

The heat exchanger 14a comprises one desirable means of thus inducing laminar flow in a tubular enclosure and includes a chambered base and a novel porous body 14c which may, for example, consist of a sintered metal produced from metal particles having binder coated surfaces. This arrangement is shown in detail in FIGURE 5 and as noted therein 14c denotes the sintered bronze portion of heat exchanger 14a formed in the shape of a cylindrical layer or disc. This body is fitted inside the tubular enclosure 2 and is solidly bonded at the upper side of the base component 14b. The base 14b is formed with chamber 14d into which gas is supplied from the compressor 4' through a conduit 20a. The base 14b is preferably comprised of a metal such as copper and is further formed at its upper portion with a number of openings as 14e, 14f, 14g, etc. which communicate with the porous undersurface of the sintered metal disc and thus provide for circulating a flow of gas into and through the sintered body at substantially all points therearound.

The sintered body 14c provides a multiplicity of substantially uniformly sized passageways each of which are characterized by substantially equivalent frictional flow resistance which may be desirably employed to induce a positive laminar flow pattern of gas inside the tubular enclosure. It is pointed out that gas is supplied under pressure through the passageway 14a and then into the openings 14e, 14f and 14g in a turbulent state. As it passes through the multiplicity of openings in the sintered body the flow of gas is smoothed out and travels along parallel paths of flow both inwardly and outwardly as indicated diagrammatically by the arrows V and W in FIGURE 5 and a laminar flow pattern is thereby produced.

Flow of compressed gas from compressor 4' is controlled by valve 10' and 12'. Located between the heat exchanger 14a in the volume 2' and valve 10' and 12' is a regenerator 20. The valves 10' and 12' are regulated to let gas in and out of the regenerator and heat exchanger 14a giving up refrigeration as the gas expands at the end of the volume 2 where the heat exchanger 14a is located.

As the gas expands it may absorb heat from any desired heat load. In the drawings one typical heat load is diagrammatically indicated by the member Q which can, for example, be a solid body or a conduit for receiving therethrough a fluid body.

The tube wall along its length in the direction from 14a to 14' varies in temperature between certain limits. Each of the wall temperature values remain essentially constant. The gas, however, as it moves along the walls changes in temperature as a function of pressure.

As noted above a novel heat exchanger mechanism is set up to provide transfer of heat from the entrance end of the volume 2 to the far end. This is due to a heat exchange between the gas in the tube and the walls of the tube. When the gas is at high pressure it is hotter than the tube wall all along the tube and a heat transfer from gas to wall occurs. When, however, the gas is at low pressure the temperature of gas is lower than that of the tube wall and a heat transfer all along the tube from wall to gas occurs.

However, the quantity Q of heat picked up by a corresponding small portion of the gas is transferred back to the wall at a location on the tube further along the tube towards the heat exchanger 14' at the opposite end thereof. In this way heat is pumped from the flow smoothing

heat exchanger 14a to the heat exchanger 14' in the far end of the tube, thus providing an increased refrigerating effect at the flow smoothing heat exchanger 14a, and also providing an increased heating effect at the opposite end heat exchanger 14'. This is best achieved when the flow of gas in the tube is essentially laminar in nature. Thus all the surfaces of the chamber walls serve in the same capacity as heat exchangers 14a and 14'. By this means heat may be pumped against a large temperature difference between the tube ends even though the pressure fluctuation is so small that no gas portion is moved all the way through the distance between the heat exchangers 14a and 14'.

In FIGURE 4 there is illustrated another form of the invention consisting of a multi-stage unit. As shown therein numeral 23 denotes a piston driven by a crank C mounted for reciprocation in a cylinder 24. This arrangement may be employed to move gas into an out of an enclosed volume in the same general manner as accomplished by the valves 10 and 12 of FIGURES 1 and 3. FIGURE 4 also illustrates one suitable way of interconnecting a plurality of systems like that of FIGURE 3 in order to obtain progressively lower temperatures. Raising and lowering pressure occurs simultaneously in successive stages. The additional stages do not require any additional low temperature moving parts but involve only additional volumes, heat exchangers and regenerators.

Considering FIGURE 4 more in detail, the piston 23 provides a flow of compressed gas through conduit 25 into a first regenerator 26a. A portion of the gas moves through the conduit 27 and then through a second regenerator 26b. Another portion of the gas moves through a branch conduit 29 and a fluid smoothing heat exchanger 30a to a first enclosed volume 28a. At the opposite end of volume 28a is a hot end heat exchanger 32a which is cooled by suitable cooling means 34.

A compressed portion of the gas is heated and gives up heat to the hot end heat exchanger 32a. Thereafter, this portion of gas expands and becomes cooled as it passes through the flow smoothing heat exchanger 30a and is at a temperature lower than the temperature at which it entered volume 28a. This produces a refrigerating effect on heat exchanger 30a. This refrigeration may then be used by connecting a thermal conducting element 37a to the heat exchanger 30a above-noted and to a heat exchanger 32b in a second enclosed volume 28b, to pre-cool heat exchanger 32b to a temperature lower than the reference room temperature.

Volume 28b operates in a similar manner to volume 28a except that the gas entering its cooled end flow smoothing heat exchanger 30b through conduit 31 and ultimately heat exchanger 32b has been pre-cooled further by regenerator 26b. A thermal conducting element 37b connects with an enclosed volume 28c.

Volume 28c also operates similarly to volumes 28a and 28b except that gas which is to enter cooled end flow smoothing heat exchanger 30c and ultimately hot end heat exchanger 32c first passes through regenerator 26c where it is further cooled. A thermal conducting unit 37c connects with a fourth enclosed volume 28d.

Volume 28d again operates similarly except that gas entering flow smoothing heat exchanger 30d and hot end exchanger 32d through conduit 39 is still further cooled by regenerator 26d. A thermal conducting element 37c connects with heat exchanger 32d.

It should be observed that the gas flow through the system is not interrupted by any valve except the one inlet and the one outlet valve shown in FIGURES 1 and 3 and with respect to FIGURE 4 a free flowing uninterrupted circuit exists at all points in the system. In FIGURE 4 no valve at all is used.

As an example of temperatures which may be achieved with a device of the type shown in FIGURE 3, assuming heat exchanger 14' is maintained at 70° F., it is possible to cool heat exchanger 14a to -200° F. and lower. This

may be accomplished in a matter of a few minutes or somewhat longer depending upon the diameter of the tube used and the cycles per minute of the pressure oscillation. When a heat load Q member is attached to heat exchanger 14a, heat will be removed from the heat load member and it will be cooled. It should be noted that temperatures of -200° F. and lower may be achieved with relatively small compression ratios and relatively high thermal efficiency may be achieved.

In the multi-stage type of apparatus of the invention shown in FIGURE 4 the temperature drop ratio achieved in the single stage unit may be multiplied. By means of a multi-stage unit, as shown in FIGURE 4, one can step the temperature down from that achieved by a single stage unit to any temperature in which a thermal regenerator can operate, i.e., 10° – 15° K. A two-stage unit can readily achieve 80° K. and a little lower in some cases; a three-stage unit can achieve 40° K., etc.

The heat exchanger 14a and its associated heat load Q, together with the regenerator 20, may preferably be insulated to prevent extraneous heat leak to thus cause a parasitic heat load on the refrigerator. The insulating effect may be accomplished by any standard insulating material or a high vacuum enclosure or in other ways.

Similarly, the invention is not limited to the specific form of gas compressing means disclosed, but may be embodied in a system wherein the gas volume is moved by other types of displacement mechanisms than those shown in FIGURES 1, 3 and 4.

In place of the sintered metal, I may desire to accomplish flow smoothing of a gas in other ways as, for example, by means of a disc formed with very fine holes arranged to form substantially uniformly sized passageways. For example, a comminuted mass of non-metal material coated with a binder may be processed to form a smoothing flow body.

Various other changes and modifications may be resorted to within the scope of the appended claims.

I claim:

1. Method of refrigeration which comprises supplying gas along a path of free flow through a thermal regenerator and a first heat exchanger and through a porous body to achieve laminar flow as it moves then into one end of an enclosed gas filled volume thereby compressing the gas already in the said gas filled volume and causing a continuous increase in temperature in all the gas while it is being supplied and as it is compressed into the opposite end of the enclosed volume, removing heat from said gas in a second heat exchanger at the said opposite end of said enclosed volume at a temperature higher than the temperature of the gas entering said enclosed volume and leaving said first heat exchanger, then expanding said gas in said enclosed volume thereby to cause a progressive decrease in temperature as the compressed gas expands away from the said opposite end of the enclosed volume and discharges through the said first heat exchanger and regenerator, and adding heat from a refrigeration load located adjacent to the said first heat exchanger to the exhausting gas as it passes through said first heat exchanger in an amount equivalent to the said heat removed from the gas in the said second heat exchanger and at a temperature lower than that of the said second heat exchanger.

2. A refrigeration method which comprises varying the pressure in an enclosed gas filled fixed volume by introducing and removing gas from one end of the gas filled fixed volume through a regenerator along a free flowing path while inducing temperature changes as the gas is removing heat at a heat sink temperature at an opposite end of the gas filled volume and adding heat from a refrigeration load imposed adjacent to said first end of the gas filled volume at a temperature lower than the temperature of the said heat sink temperature.

3. Method of refrigeration which comprises supplying gas continuously in a free flowing uninterrupted path

through a thermal regenerator and a first heat exchanger at one end of an enclosed gas filled fixed volume thereby compressing the gas already in the gas filled fixed volume and causing an increase in temperature in the said gas filled volume at the points where it is compressed into the opposite end of the gas filled volume, then removing heat from said gas in a second heat exchanger at said opposite end of said gas filled volume and at a temperature higher than the temperature of the said first heat exchanger, and exhausting said compressed gas through said first heat exchanger and absorbing heat at the point of exhausting.

4. A method according to claim 1 in which the gas is confined in a plurality of volumes each of which function in a progressive manner such that heat is pumped from one volume to another and successively lower temperatures are achieved.

5. Method of refrigeration which comprises increasing and decreasing the pressure of gas in an enclosed volume by supplying and exhausting gas from an entrance end of the volume through a thermal regenerator such that when pressure is low heat is transferred from the walls of the volume to the gas and when pressure is high heat is transferred from the gas to the walls at points further away from the entrance and exhausting end of the volume, whereby heat is pumped away from the entrance end against a large temperature gradient in which the flow is in a laminar flow pattern and the laminar flow pattern is achieved by moving the gas through a multiplicity of substantially uniformly sized openings.

6. Method of refrigeration which comprises increasing and decreasing the pressure of gas in an enclosed volume by supplying and exhausting gas from an entrance end of the volume through a thermal regenerator such that when pressure is low heat is transferred from the walls of the volume to the gas and when pressure is high heat is transferred from the gas to the walls at points further away from the entrance and exhausting end of the volume, whereby heat is pumped away from the entrance end against a large temperature gradient in which the flow is in a laminar flow pattern and the laminar flow pattern is achieved by moving the gas through a multiplicity of substantially uniformly sized openings which are comprised by a sintered metal disc.

7. In a method of the class described the steps which include containing a volume of gas in a tubular enclosure, introducing into the tubular enclosure another volume of gas which is directed along paths of flow extending substantially parallel to the longitudinal axis of the tubular enclosure, compressing the volume of gas already in the enclosure body thereby to increase the gas temperature, inducing a flow of heat from the compressed gas through the walls of the tubular enclosure at one end thereof, then expanding all of the gas in the tubular enclosure to lower its temperature and exhausting portions of the gas from the tubular enclosure thereby to induce a flow of heat from the tubular enclosure to the gas at points of emission from the enclosure.

8. In a method of the class described, the steps which include containing a volume of gas in a tubular enclosure having at one end thereof gas passageways which extend parallel to the longitudinal axis of the tubular enclosure, supplying another volume of gas under pressure through a thermal regenerator and then through the said gas passageways to cause the gas to enter the tubular enclosure along paths of flow which are substantially parallel to the axis of the enclosure, compressing the gas already in the enclosure body and inducing an increase in temperature whereby heat is pumped from the tubular enclosure.

9. A device of the class described comprising tubular enclosure means for supplying gas under pressure through a thermal regenerator and flow smoothing heat exchanger comprising a porous gas permeable body to the tubular enclosure at one end thereof, means for removing heat

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at the far end of the enclosure to produce heating.

10. A device of the class described comprising tubular enclosure means for supplying gas under pressure through a thermal regenerator and flow smoothing heat exchanger to the tubular enclosure at one end thereof, means for removing heat at the far end of the enclosure to produce heating and means for absorbing heat in the flow smoothing heat exchanger to produce cooling at relatively low temperature.

11. A structure as defined in claim 10 in which a heat load is connected to the said flow smoothing heat exchanger.

12. A structure as defined in claim 10 in which the flow smoothing heat exchanger comprises a cylindrical body having a passageway extending through one peripheral side of the body to communicate with a chamber therein, a sintered metal disc supported on said member and a plurality of passageways for permitting circulation of gas entering the peripheral passageway to move into contact with the sintered metal disc and pass therethrough.

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13. Method of refrigeration which comprises increasing and decreasing the pressure of gas in an enclosed volume by supplying and exhausting gas, flowing through a porous body to produce essentially laminar flow, from an entrance end of the volume through a thermal regenerator such that when pressure is low heat is transferred from the walls of the volume to the gas and when pressure is high heat is transferred from the gas to the walls at points further away from the entrance and exhausting end of the volume, whereby heat is pumped away from the entrance end against a large temperature gradient.

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