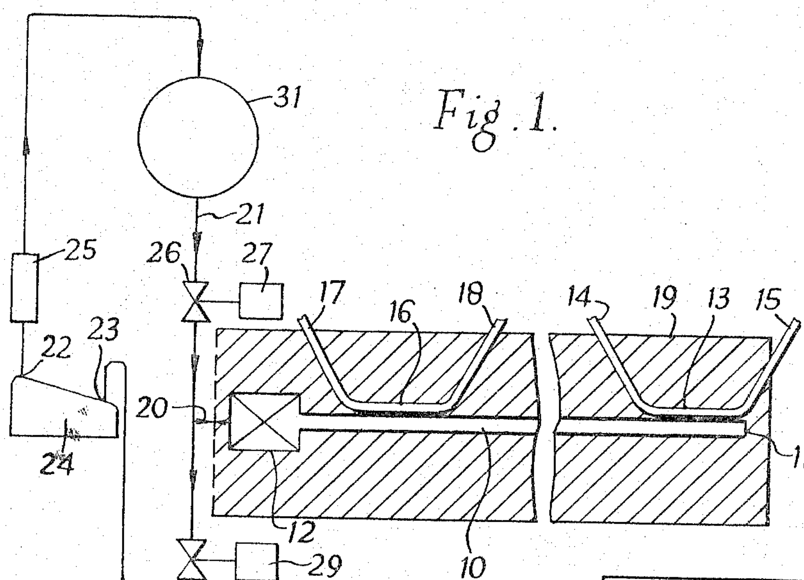
31
21
25
26
27
17
16
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13
15
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23
20
24
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12
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10
28
21
32

Fig. 1.

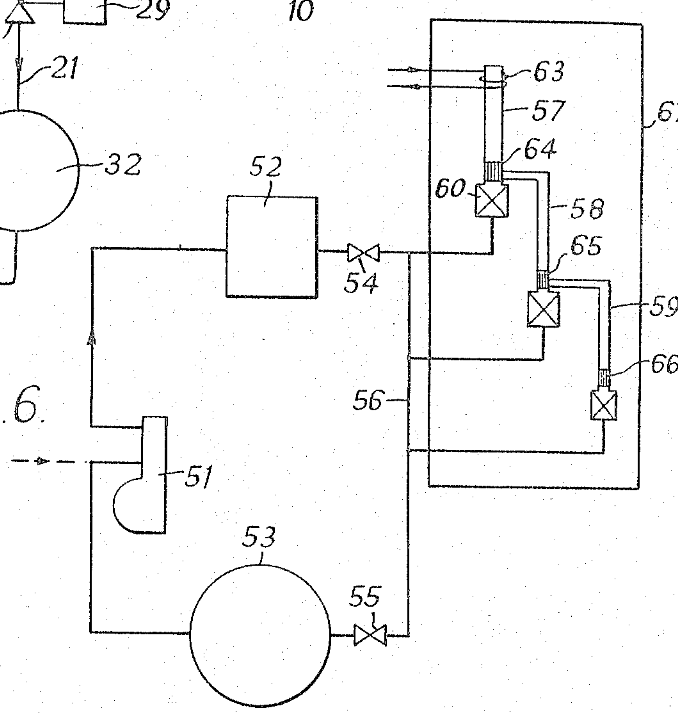

63
57
67
64
52
60
58
65
54
59
66
56
51
53
55

Fig. 6.

Feb. 7, 1967 H. J. T. SMITH 3,302,422

REFRIGERATION APPARATUS

Filed April 7, 1964 3 Sheets-Sheet 2

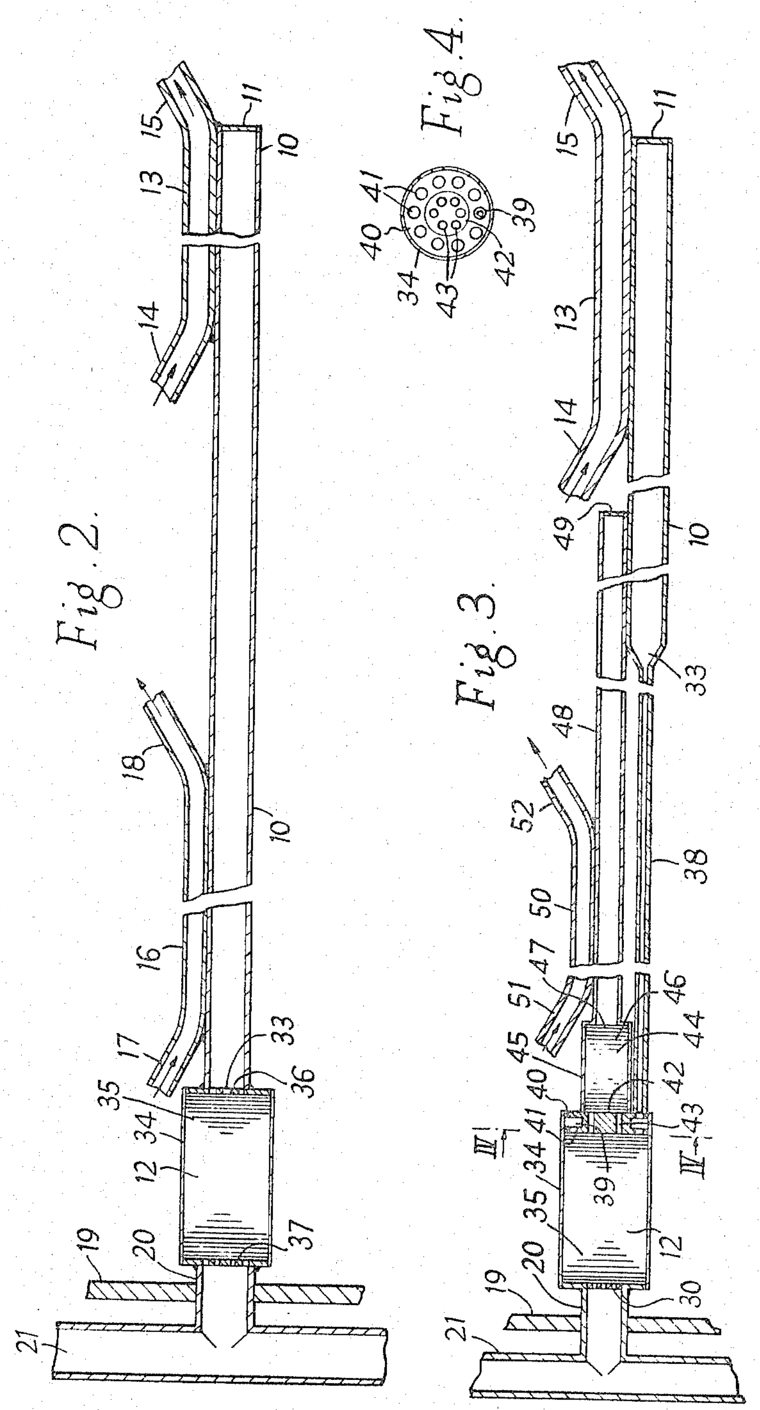


Fig. 2. Fig. 3. Fig. 4.

Feb. 7, 1967 H. J. T. SMITH 3,302,422

REFRIGERATION APPARATUS

Filed April 7, 1964 3 Sheets-Sheet 3

Fig. 5A.

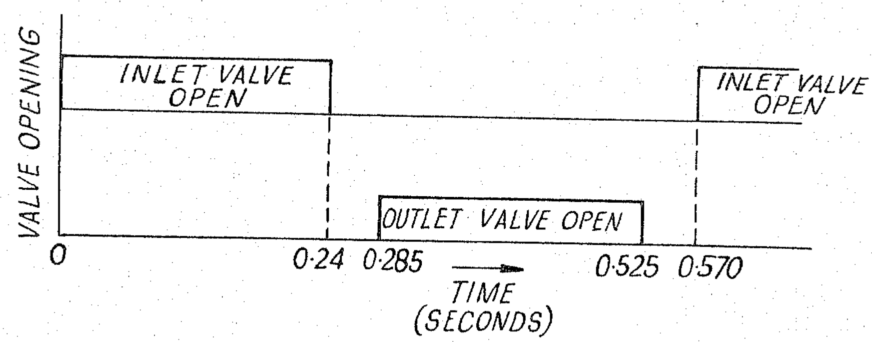



Fig. 5B.

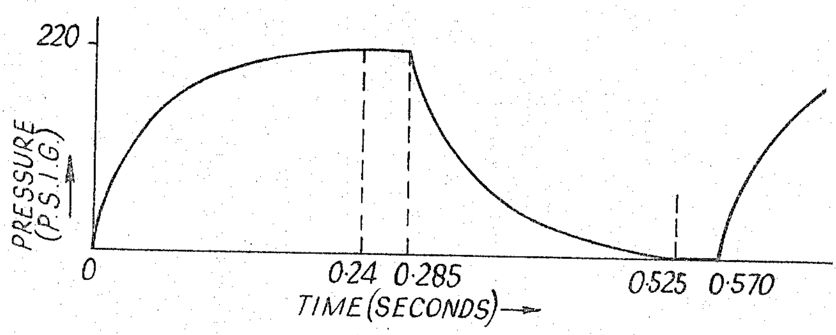
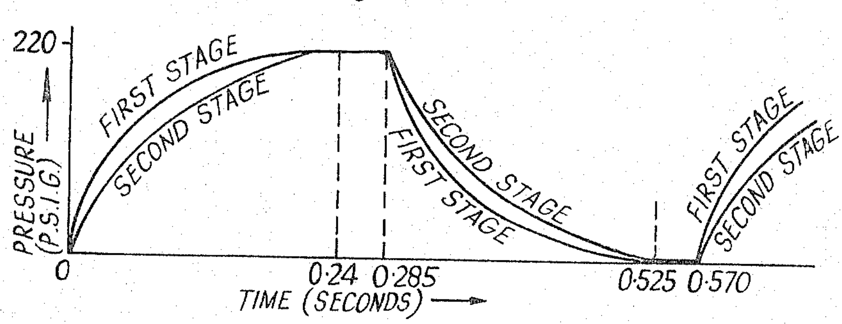



Fig. 5C.



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3,302,422

Patented Feb. 7, 1967



3,302,422

# REFRIGERATION APPARATUS

Howard John Treweek Smith, Bognor Regis, Sussex, England, assignor to Petrocarbon Developments Limited, London, England, a British company

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18 Claims. (Cl. 62—86)

This invention is concerned with improved refrigeration appartus, and with an improved method of producing refrigeration.

Refrigeration at low temperatures of the order of 200° K. and down to very low temperatures of the order of 15° K., is required in small quantities, for an increasing number of scientific purposes, for example, for use in connection with infra-red detectors, masers and cryotrons. The usual methods of producing refrigeration for these purposes are either by expansion using a piston expansion device or by expansion through a Joule-Thomson valve. The first method has the disadvantage that it involves parts moving at low temperatures, while the second method has the disadvantages that it involves very high pressures, of about 2,000 pounds per square inch and that, if it is to be operated in more than one stage, different working gases are usually required in the several stages.

It is an object of this invention to provide refrigeration at low or very low temperatures which includes no mechanical parts moving at low temperatures, which operates at relatively low pressures, e.g. pressures not above 300 p.s.i.g., and which can operate in stages without requiring the use of different working gases in the several stages.

The present invention includes refrigeration apparatus comprising a tubular member which is open at one end and closed at the other end, a thermal regenerator in communication with the open end of the tubular member, a gas conduit in communication with the thermal regenerator so that gas under pressure may be passed from the gas conduit through the thermal regenerator to the tubular member and exhausted with expansion from the tubular member through the thermal regenerator to the gas conduit, the thermal regenerator serving to abstract heat from gas entering the tubular member and return heat to gas leaving the tubular member, valve means in said gas conduit for controlling the flow of gas to and from the tubular member and arranged to permit the gas to enter and leave the tubular member as a succession of charges and heat exchange means adjacent the closed end of the tubular member for enabling a coolant to be passed in thermal contact with the tubular member adjacent to the closed end thereof, whereby on operation of the apparatus with gas under pressure being fed into, and exhausted with expansion from, the tubular member as a succession of charges and with a coolant passing through the said heat exchange means refrigeration is made available near the open end of the tubular member adjacent the thermal regenerator.

The present invention includes also a method of producing refrigeration which comprises repeatedly performing the cycle of admitting compressed gas to a relatively long and narrow chamber through an inlet situated at one end thereof, with abstraction of heat from the gas before it enters the chamber abstracting heat from the chamber near the end thereof remote from the inlet, and exhausting compressed gas from the chamber with expansion thereof within the chamber and with return of abstracted heat to the gas after it leaves the chamber, whereby refrigeration is made available at the end of the chamber adjacent the inlet.



The invention includes further a unit for use in refrigeration apparatus, comprising a tube open at one end and closed at the other end, heat exchange means secured to the tube in thermal contact therewith adjacent its closed end, a housing with an opening at each end secured to the tube in communication with the open end of the tube and heat-absorbing packing within the housing for abstracting heat from gas entering the tube and for delivering heat to gas leaving the tube.

The invention will now be described, by way of example, with reference to the accompanying drawings in which:

FIGURE 1 is a diagrammatic view of a single stage refrigeration apparatus according to the invention;

FIGURE 2 is a longitudinal section through a part of the apparatus shown in FIGURE 1;

FIGURE 3 is a longitudinal section through part of a two-stage refrigeration apparatus according to the invention;

FIGURE 4 is a cross-section on the line IV—IV of FIGURE 3; and

FIGURE 5 is a diagram of the valve timings adopted and pressure changes occurring in a typical operation of the apparatus illustrated in FIGURES 1 and 2 and in FIGURE 3.

FIGURE 6 is a schematic view of a three-stage refrigeration apparatus in accordance with the invention.

Referring to FIGURE 1, the refrigeration apparatus includes an elongated tube **10**, which is closed at its end **11** and communicates at its other end with a thermal regenerator **12**. A first heat exchange means **13**, through which a coolant fluid may be circulated by connecting pipes **14**, **15** is secured to the tube **10** near its closed end **11** in thermal contact therewith. A second heat exchange means **16** is similarly secured to the pipe **10** adjacent the thermal regenerator **12** and is provided with connecting pipes **17**, **18** for circulating a fluid to be used as a refrigerant therethrough.

The elongated tube **10**, thermal regenerator **12** and heat exchange means **13** and **16** are encased within a thermal insulating box **19** which may be packed with insulating material or be under high vacuum.

The thermal regenerator **12** communicates via pipe **20** with a pipe line **21** communicating at one end with the outlet **22** and at its other end with the inlet **23** of a gas compressor **24**. An after-cooler **25** is provided on the outlet side of compressor **24** to remove heat of compression from gas compressed by the compressor.

An inlet valve **26** arranged to be operated by a solenoid **27** to move from the fully open to the fully closed position and vice versa is set in gas line **21** and between compressor outlet **22** and tube **10**, while an outlet valve **28** also arranged to be operated by a solenoid **29** to move from the fully open to the fully closed position and vice versa is set in gas line **21** and between tube **10** and compressor inlet **23**. A gas reservoir **31** is included in line **21** between compressor outlet **22** and inlet valve **26**, while a further gas reservoir **32** is included in line **21** between outlet valve **28** and compressor inlet **23**, these reservoirs serving in use as buffers to eliminate fluctuation in pressure of gas admitted to tube **10** through inlet valve **26** or exhausted from tube **10** through outlet valve **28**.

The structure of tube **10** is shown in greater detail in FIGURE 2, in which the reference numerals used in FIGURE 1 are used for the same parts. Tube **10**, which is made of stainless steel, is of circular cross section having an internal diameter of ⅜" and a wall thickness of 1/16", and is about 2'6" long, being closed at its end **11**, as previously stated, and open at the other end **33**, at which it is welded to one end of the regenerator 12 comprising a stainless steel cylinder 34 of about 1" diameter and 2" long, packed with 400–500 discs 35 of 200 mesh stainless steel gauze. Each disc 35 extends transversely of cylinder 34, and the total weight of the discs is about 45 grams. An apertured cover plate 36 extends across the end of cylinder 34 so as to prevent the discs from moving into the interior of tube 10 while allowing gas to flow thereto.

To the end of cylinder 34 remote from tube 10, is welded a short length of stainless steel pipe 20 which passes through the wall of insulating box 19 and communicates with gas line 21 between inlet valve 26 and outlet valve 28. Pipe 20 communicates with the interior of cylinder 34 through a cover plate 37 which is apertured similarly to cover plate 36 so as to prevent the discs from moving into pipe 20 while allowing gas to flow between the pipe and the cylinder.

The heat exchange means 13 comprises a length of stainless steel tubing about 10" long which is silver soldered to the tube 10 along the portion thereof which extends inwardly from closed end 11, and is connected by supply and return lines 14 and 15 to a source of cooling water disposed outside cold box 19. Similarly heat exchange means 16 comprises a length of stainless steel tubing about 6" long which is silver soldered to tube 10 along the portion thereof which is near open end 33 and is connected to supply and return lines 17 and 18 for circulating a cold-transferring fluid refrigerant therethrough. When the apparatus is in operation, tubing 13 constitutes a heat-sink while tubing 16 constitutes a cold-sink.

In using this apparatus for producing refrigeration, a suitable working gas is argon which has a high ratio between its specific heat at constant pressure and specific heat at constant volume, and an example of operation of this apparatus using argon will now be described.

The compressor 24 delivers argon at room temperature and a pressure of 220 pounds per square inch gauge to reservoir 31 whence argon is taken at substantially 220 p.s.i.g. according as valves 26 and 28 are opened and closed in a repeated cycle determined by the operation of the solenoids 27 and 29. In one particular cycle inlet valve 26 is opened and allowed to remain open for 0.24 second while outlet valve 28 remains closed. Consequently a charge of argon flows through pipe 20 and regenerator 12 into tube 10 until a pressure of substantially 220 p.s.i.g. is attained therein near closed end 11. The compression of argon which is in the tube at the commencement of the cycle raises the temperature of this argon and heat is transferred to the walls of the end portion of the tube 10, whence it is removed by cooling water in tubing 13 at a temperature of about 290° K.

After approximately 0.045 second from the closure of inlet valve 26, outlet valve 28 is opened and remains open for 0.24 second, while inlet valve 26 remains closed. Argon thereupon flows from tube 10 through regenerator 12 and pipe 20 to reservoir 32 and thence to the compressor inlet 23 at a pressure of almost 0 p.s.i.g. In flowing out of the tube, the compressed argon is expanded and, having lost heat to the cooling water, is thereby cooled to a temperature below room temperature. The wall of tube 10 near open end 33 is therefore cooled, and the regenerator discs 35 are also cooled.

After approximately 0.045 second from the closure of outlet valve 28, inlet valve 26 opens again and the cycle is repeated, a complete cycle therefore taking 0.57 second. Argon entering tube 10 when the cycle is repeated is initially cooled in passing through the regenerator 12 but compression of the gas in tube 10 causes heating at its end 11. Heat is removed by heat sink 13 before the gas is cooled on expansion giving up cold to the cold sink 16 and being warmed to room temperature on passing through the regenerator 12.

After approximately 60 minutes of operation, the re-



generator 12 has been cooled to a temperature of about 150° K. at the end thereof adjacent tube 10, while at its end communicating with pipe 20 the temperature of the regenerator is about 290° K., a rectilinear temperature gradient extending through the regenerator. These are equilibrium temperatures at which the regenerator is not further cooled by continued operation of the apparatus, and when equilibrium is reached, continued operation of the apparatus makes cold available to the cold sink.

Operating the apparatus as described, so that argon is taken from reservoir 31 at the rate of about 2.9 cubic feet per minute, the argon compressed at the end 11 of tube 10 attains a mean temperature of 350° K. after equilibrium is reached, while the wall of the tube near that end is maintained at about 290° K. Some improvement in heat transfer from the tube may be effected by making its warm end of a material more conductive than stainless steel, but stainless steel offers the advantage that there is no excessive conduction along the tube and the heat transfer is adequate. Near the cold end of tube 10, the wall of the tube is maintained at a temperature of 150° K., and refrigeration is delivered at this temperature at the rate of about 1 watt to a cold-transferring liquid or gas which is continuously circulated between cold sink 34 and the point at which refrigeration is required.

While specific data adopted or measured in a working model of the apparatus have been described in the above example, it will be appreciated that these figures are not critical, though indicative of ranges within which operating conditions preferably lie. For example, the dimensions of the tube may advantageously vary so as to give a cross-sectional area between one sixteenth and one half of a square inch, and a length between eighteen inches and six feet. In a relatively short tube, the cross-sectional area may be up to four square inches. Gases other than argon may be used, and in particular air may be used, being taken from an available source of compressed air and being exhausted from the tube to atmosphere.

Gas pressures used preferably lie in the range 150 to 300 p.s.i.g. The valves are suitably timed so that the apparatus operates between 200 cycles and 5 cycles a minute, a preferred rate being between 150 and 60 cycles a minute, the inlet valve preferably being open for the same length of time as the outlet valve while the interval between the closure of one valve and the opening of the other is preferably not more than 0.05 second.

It will be apparent that if heat is withdrawn from the warm end of the tube at a temperature substantially below room temperature, the cold end of the tube will be cooled to a temperature well below the 150° K. described. Cooling of the warm end to a temperature below room temperature can be achieved by coupling two or more tubes operating in a similar fashion to tube 10 so that the cold end of one cools the warm end of the next succeeding tube. Refrigeration apparatus in which two tubes are coupled in a particularly advantageous way for this purpose is illustrated in FIGURES 3 and 4.

One of the tubes illustrated in FIGURE 3 is generally similar to that shown in FIGURE 2, so like parts have been accorded like reference numerals and will not be further described. Tube 10 is spaced from regenerator cylinder 34 by a distance a little over one foot, and the open end 33 of the tube is connected to cylinder 34 of regenerator 12 by a copper tube 38 of ⅛" internal diameter. Copper tube 38 communicates with an annular channel 39 formed in a cover plate 40 of cylinder 34, channel 39 in turn communicating with the interior of the cylinder 34 through holes 41. The central portion 42 of cover plate 40 is formed with holes 43 through which gas can pass from regenerator 12 to a further regenerator 44. Regenerator 44 comprises a cylinder 45 of about ½" internal diameter and 1" long, and is made of stainless steel, being packed similarly to cylinder 34 with 200 mesh stainless steel gauze discs 46. Cylinder 45 communicates at its end remote from cylinder **34** with the open end **47** of a stainless steel tube **48** of 1/4" internal diameter and about 1'6" long which extends parallel to tube **38** and overlaps tube **10**. Tube **48** has a closed end **49**, and the end portion of tube **48** adjacent end **49** is silver-soldered to the overlapped end portion of tube **10**. A cold sink **50** about 4" long and similar to cold sink **16** shown in FIGURE 2 is silver-soldered to tube **48** near its open end **47** and has supply and return pipes **51** and **52**.

The arrangement shown in FIGURE 3 is provided with a compressor **24**, valves **26** and **28** and reservoirs **31** and **32** fitted to the pipe line **21** as shown in FIGURE 1.

In use of this two-stage apparatus, the valves **26** and **28** are opened and closed to admit argon at a pressure of 200 p.s.i.g. and exhaust argon to a pressure of 0 p.s.i.g. while the warm end-portion of tube **10** is cooled by cooling water, exactly as described for the preceding example. The portion of tube **10** adjacent open end **33** is thereby cooled, thus cooling the warm end portion of tube **48**. Thus, in tube **10** a first stage of refrigeration occurs, while in tube **48** a second stage of refrigeration occurs. In this second example, the cold-end portion of tube **48** and the adjacent regenerator packing discs **46** are in consequence cooled to a temperature of about 120° K., and when equilibrium is reached refrigeration is available at this temperature at the rate of 1.5 watts.

The valve timings and consequent changes of gas pressure within the tubes for the two stage apparatus are illustrated in FIGURES *5a* and *5c* respectively. It will be apparent that the valve timings are the same as for the single stage operation, the pressure changes for which are shown in FIGURE *5b*.

More than two tubes can be coupled together to produce still lower temperatures, down to 15° K.

A suitable arrangement of a three-stage unit is schematically illustrated in FIGURE 6, in which **51** represents the compressor (with in-built after-cooler), **52** and **53** the two reservoirs, **54** and **55** the inlet and outlet valves respectively, **56** the gas pipe line, **57**, **58** and **59** the three elongated tubular members with thermal regenerators **60**, **61** and **62** respectively. Heat is abstracted from the closed ends of tubular members **57**, **58** and **59** by indirect heat exchange at points **63**, **64** and **65** respectively and refrigeration is supplied at end **66** of tubular member **59**. **67** is the thermal insulating or cold box.

The fluid circulated through tubing **16** may be any suitable gas or liquid which does not freeze at the low temperatures attained. Nitrogen, hydrogen, argon, helium or air may, for example, be used where appropriate. An organic liquid such as acetone may be used under suitable conditions of temperature.

Instead of supplying cold to a fluid as shown at cold sink **16** in FIGURES 1 and 2, an article to be cooled to, and maintained at, a low temperature may be soldered or clamped to the tube **10** in place of the tubing **16**.

By a thermal regenerator is meant any means which is adapted in successive operations to abstract heat from, and to give up heat to, a gas passing therethrough.

The heat exchange means which may be used for the circulation of a fluid in thermal contact with the tubular member **10** may be arranged externally of the tube **10** in physical contact therewith or may be within the tube with connections leading to the outside of the tube.

I claim:

**1.** Refrigeration apparatus comprising a tubular member which is open at one end and closed at the other end, a thermal regenerator in communication with the open end of the tubular member, a gas conduit in communication with the thermal regenerator so that gas under pressure may be passed from the gas conduit through the thermal regenerator to the tubular member and exhausted with expansion from the tubular member through the thermal regenerator to the gas conduit, the thermal regenerator serving to abstract heat from gas entering the



tubular member and return heat to gas leaving the tubular member, valve means in said gas conduit for controlling the flow of gas to and from the tubular member and arranged to permit the gas to enter and leave the tubular member as a succession of charges and heat exchange means adjacent the closed end of the tubular member for enabling a coolant to be passed in thermal contact with the tubular member adjacent to the closed end thereof, whereby on operation of the apparatus with gas under pressure being fed into, and exhausted with expansion from, the tubular member as a succession of charges and with a coolant passing through the said heat exchange means refrigeration is made available near the open end of the tubular member adjacent the thermal regenerator.

**2.** Refrigeration apparatus as claimed in claim **1**, in which the tubular member is a tube of internal cross-sectional area of from one sixteenth to one half of a square inch, and of a length of from eighteen inches to six feet.

**3.** Refrigeration apparatus as claimed in claim **2**, in which the tubular member is made of stainless steel and has a wall-thickness between 0.02 inch and 0.1 inch.

**4.** Multi-stage refrigeration apparatus as claimed in claim **18**, in which the valve means include a single inlet valve and a single outlet valve common to all the tubular members and the passage means is arranged to admit gas in parallel to the tubular members.

**5.** Multi-stage refrigeration apparatus as claimed in claim **4** including first and second tubular members, and having a first thermal regenerator arranged to cool gas being admitted to the first and second tubular members, and a second thermal regenerator arranged to further cool gas being admitted to the second tubular member.

**6.** Multi-stage refrigeration apparatus as claimed in claim **5**, in which the open end of the first tubular member is spaced from the first thermal regenerator by a relatively narrow tubular gas passage, and the second tubular member extends parallel to and adjacent the tubular gas passage, a portion of the second member near its closed end overlapping a portion of the first member near its open end and adjacent portions of the first and second members being in thermal contact so that the first member provides refrigeration for the second member.

**7.** A unit for use in refrigeration apparatus, comprising a tube open at one end and closed at the other end, heat exchange means secured to the tube in thermal contact therewith adjacent its closed end, a housing with an opening at each end secured to the tube in communication with the open end of the tube and heat-absorbing packing within the housing for abstracting heat from gas entering the tube and for delivering heat to gas leaving the tube.

**8.** A method of producing refrigeration which comprises repeatedly performing the cycle of admitting compressed gas to a relatively long and narrow chamber through an inlet situated at one end thereof, with abstraction of heat from the gas before it enters the chamber, cooling gas in the chamber by indirect heat exchange near the end thereof remote from the inlet, and exhausting compressed gas from the chamber through the inlet with expansion thereof within the chamber and with return of abstracted heat to the gas after it leaves the chamber, whereby refrigeration is made available at the end of the chamber adjacent the inlet.

**9.** Refrigeration apparatus comprising a tubular member which is open at one end and closed at the other end, a thermal regenerator in communication with the open end of the tubular member, a gas conduit in communication with the thermal regenerator so that gas under pressure may be passed from the gas conduit through the thermal regenerator to the tubular member and exhausted with expansion from the tubular member through the thermal regenerator to the gas conduit, the thermal regenerator serving to abstract heat from gas entering the tubular member and return heat to gas leaving the tubular member, valve means in said gas conduit for controlling the flow of gas to and from the tubular member and arranged to permit the gas to enter and leave the tubular member as a succession of charges, heat exchange means adjacent the closed end of the tubular member for enabling a coolant to be passed in thermal contact with the tubular member adjacent to the closed end thereof whereby on operation of the apparatus with gas under pressure being fed into, and exhausted with expansion from, the tubular member as a succession of charges and with a coolant passing through the said heat exchange means refrigeration is made available near the open end of the tubular member adjacent the thermal regenerator, and a second heat exchange means which is in thermal contact with the tubular member adjacent the open end thereof, and through which a fluid may be circulated.

**10.** Refrigeration apparatus as claimed in claim **9** in which the thermal regenerator comprises a housing with an opening at each end and packed with discs of metal gauze, each disc extending transversely of the direction of gas flow through the housing.

**11.** Refrigerator apparatus as claimed in claim **9** in which the said heat exchange means for the passage of coolant includes at least one tube which extends parallel to the tubular member and in thermal contact therewith adjacent the closed end thereof.

**12.** A method of producing refrigeration which comprises repeatedly performing the cycle of admitting compressed gas to a relatively long and narrow chamber through an inlet situated at one end thereof, with abstraction of heat from the gas before it enters the chamber, cooling gas in the chamber by indirect heat exchange near the end thereof remote from the inlet, and exhausting compressed gas from the chamber through the inlet with expansion thereof within the chamber and with return of abstracted heat to the gas after it leaves the chamber, said admitting and exhausting of compressed gas being for substantially equal periods of time, whereby refrigeration is made available at the end of the chamber adjacent the inlet.

**13.** A method as claimed in claim **12**, in which the cycle is performed between 200 times and 5 times a minute.

**14.** A method as claimed in claim **12** in which the cycle is performed between 150 times and 60 times a minute.

**15.** A method as claimed in claim **12** in which the gas is admitted to the chamber at a pressure between 150 and 300 pounds per square inch.



**16.** A method as claimed in claim **12** in which the gas is argon.

**17.** A method as claimed in claim **12** in which compressed gas is simultaneously admitted to and exhausted from a plurality of chambers, and refrigeration made available at the wall of one chamber is used to cool the wall of another chamber near the end thereof remote from the inlet so that lower temperature refrigeration is made available at the wall of said another chamber adjacent the inlet thereof.

**18.** Multi-stage refrigeration apparatus comprising at least two elongated tubular members each open at one end and closed at the other end, gas passage means in communication with the open end of each tubular member through a thermal regenerator whereby gas under pressure may be passed from the gas passage means through the thermal regenerator into each tubular member and exhausted with expansion from the tubular member back through the thermal regenerator and through the gas passage means, the thermal regenerator in each case serving to extract heat from the gas entering the tubular member and returning heat to the gas leaving the tubular member, valve means for controlling the admission of gas to, and exhaustion of gas from, the tubular members, the valve means being arranged to permit the gas to enter and leave the tubular members as a succession of charges, and means for the passage of coolant in thermal contact with a first tubular member adjacent the closed end thereof, the part of each succeeding tubular member adjacent its closed end being thermally linked to the part adjacent the open end of the preceding member for indirect heat exchange therewith, whereby a succession of admissions of gas under pressure to the tubular members with exhaustion and expansion after each admission and with passage of coolant through the means in contact with the said first tubular member adjacent its closed end during such operation, refrigeration is made available for use adjacent the open end of the last tubular member.


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WILLIAM J. WYE, *Primary Examiner.*