Oct. 28, 1969 E. G. U. GRANRYD 3,474,641

HEAT-ACTUATED REGENERATIVE COMPRESSOR SYSTEM

Filed Jan. 18, 1968 3 Sheets-Sheet 1

Fig.1.

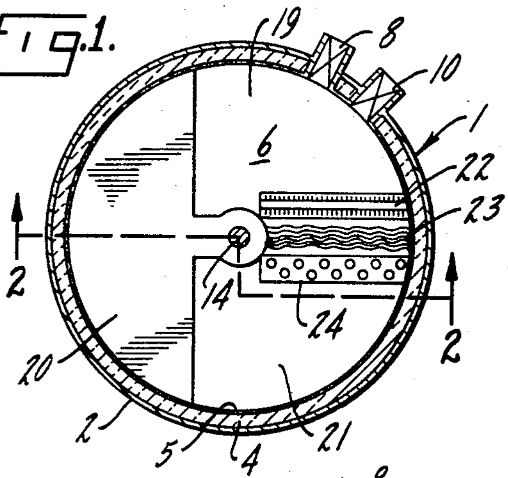

Fig.2.

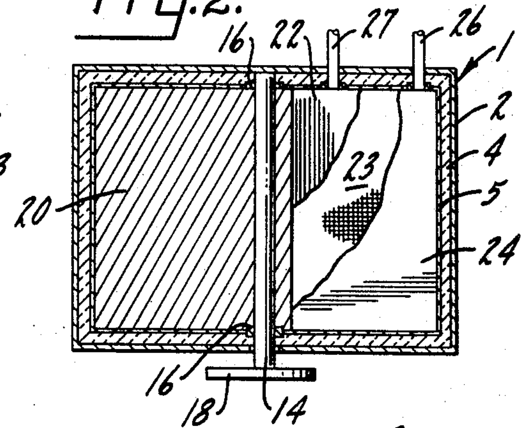

Fig.3.

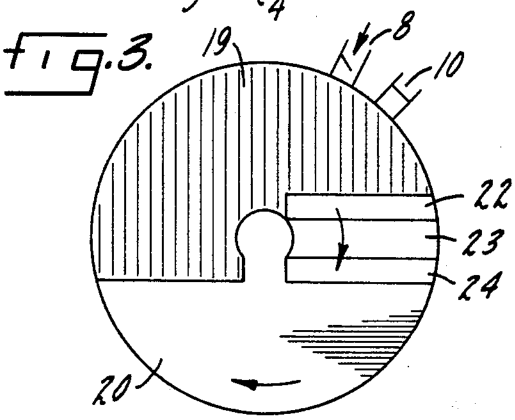

Fig.4.

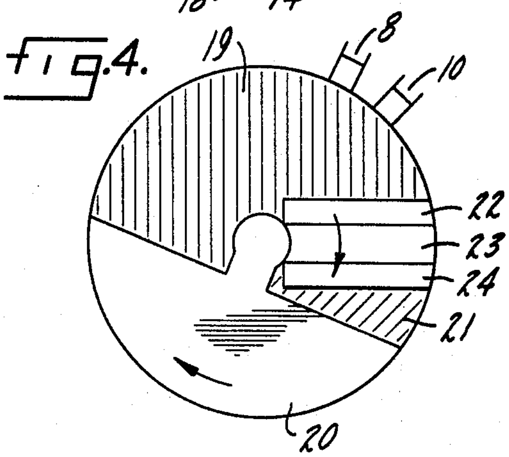

Fig.5.

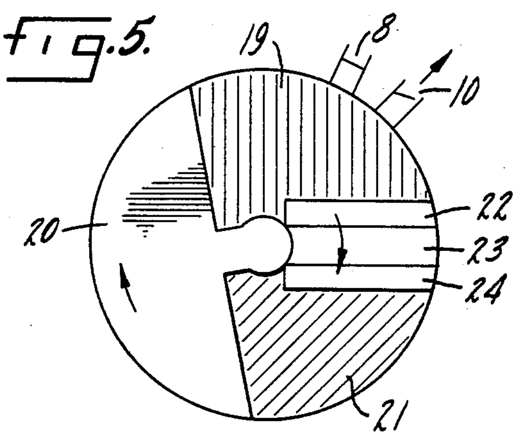

Fig.6.

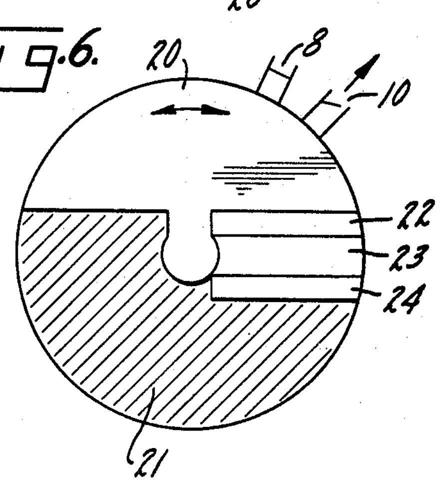

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Fig. 7.

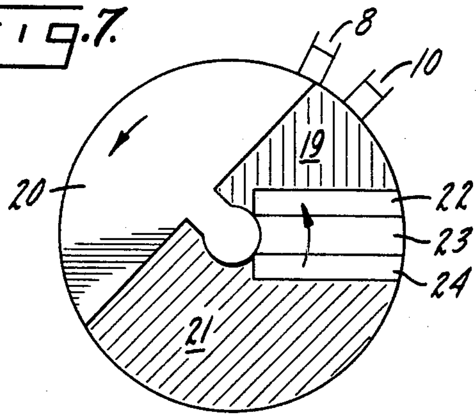

Fig. 8.

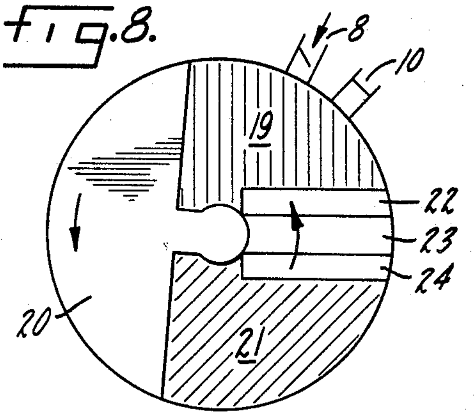

Fig. 9.

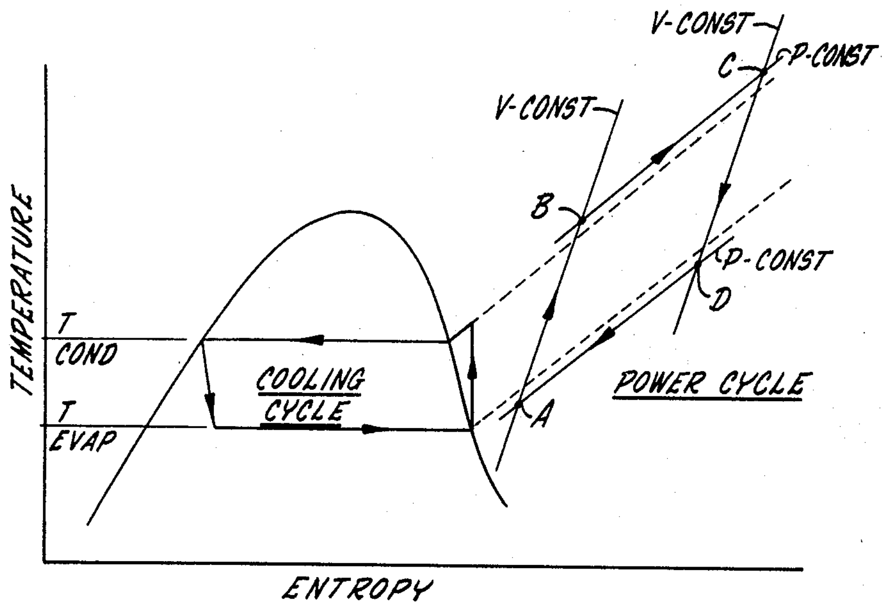

Fig. 10.

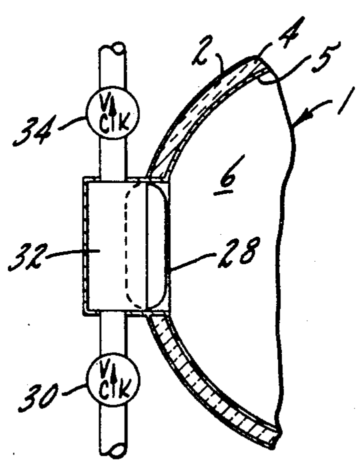

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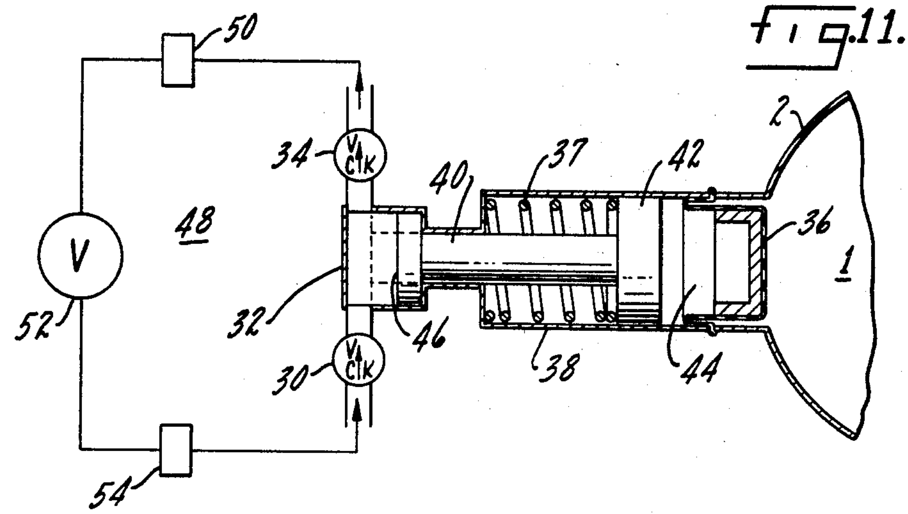
Fig. 11.



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HEAT-ACTUATED REGENERATIVE COMPRESSOR SYSTEM

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U.S. Cl. 62—498 17 Claims

ABSTRACT OF THE DISCLOSURE

A heat-actuated regenerative compressor for operation between fixed pressures, having a generally cylindrical chamber containing a readily compressible gas exhibiting high thermal conductivity and specific heat ratio which gas is cycled by an oscillatory displacer in order through a cooler, regenerator and heater within the chamber resulting in an average higher temperature-pressure relation of the total contained gas, and recycled in the opposite direction and order through the same heater, regenerator and cooler resulting in an average lower temperature-pressure relation of the total contained gas. Mechanical energy is obtained by response to such pressure changes. A dual gas cooling system comprising such a heat-actuated regenerative compressor containing a thermally efficient gas providing energy for moving a highly efficient refrigerant through a condenser-expansion-evaporation-compression cooling cycle.

BACKGROUND OF INVENTION

Heretofore heat-actuated regenerative compressors have been used in the art to compress gases for operating turbines or other devices requiring a source of high-pressure gas. Two such compressors are described in U.S. Patents 2,157,229 and 2,992,536. The prior art compressors of the general design exemplified by these patents have not proved to be very efficient apparatuses, and have experienced limited usefulness due to their relative size and the external placement of the component parts. Such prior art compressors were cylindrical with a reciprocating piston which functioned as a gas displacer. Heaters, coolers and heat-regenerators were placed external to the cylinder. The configuration of the prior apparatus resulted in a high dead volume within the heater-regenerator-cooler portion in comparison with the total volume resulting in an inefficient and commercially impractical apparatus.

The heat-actuated regenerative compressors of the prior art have not been employed in a manner to efficiently obtain a useable output of mechanical energy. Further, they have not been utilized in refrigeration systems employing efficient refrigerants.

DESCRIPTION OF INVENTION

My invention comprises a novel configuration of components having minimal dead volume and providing movement of gas through such components by oscillatory motion resulting in a heat-actuated regenerative compressor which is efficient and lends itself to commercial utilization. Further, my invention comprises a heat-actuated regenerative compressor in combination with a pressure sensitive means for conversion of energy derived from heat into mechanical energy. The compressor of my invention may be used as a prime mover. Still further, my invention comprises the novel heat-actuated regenerative compressor in combination with a cooling system in which a gas having a high thermal-conductivity and specific heat ratio is used in the heat-actuated regenerative compressor which serves through a pressure sensitive means to pump an efficient refrigerant having a high specific heat of vaporization through a condenser-expansion-compression cooling cycle.

It is an object of my invention to provide a cooling apparatus comprising a heat-actuated regenerative compressor to drive a refrigerant through a condenser-expansion-evaporation-compression cycle, wherein a first gas having suitable properties for the heat-actuated regenerative compressor portion is used in the compressor and a second gas having suitable refrigerant properties is used in the cooling portion.

It is another object of my invention to provide a heat-actuated regenerative prime mover which may be used to furnish mechanical energy.

It is a further object of my invention to provide a heat-actuated regenerative compressor containing heating, regenerative and cooling thermal exchangers within the active volume of the compressor and wherein gas is moved through such thermal exchangers in alternately opposite directions by oscillator motion.

These and other important objects of the invention will become apparent from the following description taken in conjunction with the drawings wherein:

FIGURE 1 is a plan view, in cross-section of the heat-actuated regenerative compressor of this invention;

FIGURE 2 is a side sectional view of the heat-actuated regenerative compressor as shown in FIGURE 1;

FIGURES 3 through 8 inclusive schematically illustrate the operating principles of the novel compressor of this invention;

FIGURE 9 is a graph illustrating the thermal-energy property of the cooling apparatus of this invention;

FIGURE 10 is a specific embodiment showing use of the compressor of this invention is combination with a pneumatic fluid system; and

FIGURE 11 illustrates the cooling system of the invention in a specific embodiment.

Referring specifically to FIGURES 1 and 2, the components of the heat-actuated regenerative compressor are shown as compressor **1** comprising outer shell casing **2**, insulation **4**, and inner shell casing **5** defining gas chamber **6** which is generally cylindrical in shape. Communicating from chamber **6** to external reservoirs are check-valved conduits **8** and **10**, **8** allowing only for the flow of gas into chamber **6**, and **10** allowing only for the flow of gas from chamber **6**.

Shaft **14** is disposed through chamber **6** and is retained in suitable rotatable relationship by bearing means **16**. Shaft **14** penetrates casing **5** in fluid-tight relationship and is connected through suitable linkage means **18** to power source which causes shaft **14** to undergo an oscillating movement. Secured to shaft **14** is displacer **20** which is semi-arcuate in configuration and congruent with inner shell casing **5**. Displacer **20** divides chamber **6** into substantially two volumes, a first or "cold" section **19** and a second "hot" section **21**. To furnish thermal isolation of cold section **19** from hot section **21**, displacer **20**, insulation **4**, and inner casing **5** are constructed from a thermal insulating material. Many suitable materials, such as ceramics or fused silica glass, are well known in the art.

Positioned within chamber **6** from inner shell casing **5** toward the center of chamber **6**, juxtaposed and extending substantially the entire length of chamber **6** separating cold section **19** from hot section **21** are cooling means **22**, heat-regenerative means **23** and heating means **24**. Each of the thermal exchangers are constructed of materials having suitable thermal properties such as copper, stainless steel, Hastalloy, or ceramics. Also, each of the thermal exchangers is designed to have maximal frontal area consistent with suitable thermal exchange properties to minimize the pressure drop of gas by movement through the thermal exchangers. It is also desired to have minimal dead gas volume contained within the thermal exchangers.

Cooling means **22** is constructed of a suitable metal for containment of the cooling media and meeting the above requirements. It has been found that flat duct type coolers result in minimal dead volume. Narrow spacing is essential for the desired high thermal transfer coefficients. Finned cooler configurations with close spaced fins may also be utilized to result in high heat transfer with low dead volume. Cooling fluid from an external source is circulated throughout cooling means **22** by introduction and exit at conduit **27** which is two concentric tubes. It should be understood that all penetrations of casing **5** are made in gas-tight fashion.

Heating means **24** is preferably a tube bundle heater and may be supplied with heat obtained by combustion of natural fuels such as gas fired from within or, alternatively, electrically heated, or as shown, may utilize a heat transfer fluid by introduction and exit via conduit **26**. Increased heat transfer within heating means **24** may be achieved by employing extended surfaces attached to the tubes and use of radiation shields of wire cloth surrounding heater tubes which additionally prevents radiation from unduly heating the adjacent areas.

Regenerator means **23**, positioned between cooling means **22** and heating means **24**, is a thermal storage and exchange section of the thermal exchangers and is preferably flat or corrugated stainless steel wire cloth or fine wire mesh arranged in successive layers with no thermal contact between layers. Such a configuration provides for a thermal gradient in the regenerator between cooling means **22** and heating means **24**. The use of fine wire and close weaving regenerator construction provides small void volume in regenerator **23**.

Briefly, operation of compressor **1** is achieved by oscillation of displacer **20** moving gas from cold section **19** through the cooler-regenerator-heater into hot section **21** at an average higher temperature-pressure relationship and then returning the gas from hot section **21** back through the heater-regenerator-cooler to cold section **19** at an average lower temperature-pressure relationship. The pressure in sections **19** and **21** is maintained about equal, except for the pressure drop through the thermal exchangers. Due to the low pressure drop in the thermal exchangers, a very small power input is required to oscillate displacer **20**. In fact, in use, the energy input required for displacer oscillation is in the order of 0.1 percent of the total energy input to the compressor, the major energy input being heat to heating means **24**. The total energy input requirement of the compressor is further minimized by use of heat regenerator **23** which has been found in practice to be at least 80 percent efficient in take-up, storage, and release of thermal energy. A high temperature ratio between hot section **21** and cold section **19** is desirable.

The compressor of this invention may be operated by use of various gases having the desired physical characteristics set forth above. Inert gases including helium, neon, argon, krypton and xenon are preferred gases. Either a single gas or mixtures of different gases may be used. I have found helium to be especially useful in the compressor of this invention.

For more detailed description of the operation of the compressor of the invention, reference is made to FIGURES 3–8 showing a system wherein the gas in the heat-actuated compressor is the material used in the associated system, such as a cooling system. In FIGURES 3–8, the arrows indicate direction of gas flow and direction of displacer movement. Vertical lines indicate the volume of gas in cold section **19** and the angular cross-hatched section indicates the volume of gas in hot section **21**. When average temperatures are referred to they are the mass average absolute temperatures of all gas contained in the compressor, including gas contained in the thermal exchangers.

Referring specifically to FIGURE 3, the maximum amount of gas is contained in cold section **19** at a slightly lower pressure than the external reservoir pressure, and due to this pressure difference, gas flows into chamber **6** from conduit **8**. Displacer **20** actuated by an independent power source moves in the clockwise direction forcing the contained gas through cooler **22**, regenerator **23**, and heater **24**. The temperature of the gas moving in a clockwise direction through the thermal exchangers is raised. The mass average temperature of the entire gas system is also raised. In FIGURE 4, partial movement of displacer **20** is shown and the concomitant rise in temperature causes an increase in pressure of the contained gas to equal the external reservoir pressure and the gas flow into chamber **6** from conduit **8** stops. Displacer **20** continues clockwise movement as shown in FIGURE 5 thereby moving more gas through the thermal exchangers raising the mass average temperature and pressure. After exceeding the pressure of the external reservoir there is outward flow of gas through conduit **10** in order to maintain relatively constant pressure in chamber **6**.

The temperature-pressure relationship of the gas continues to increase as displacer **20** moves to the end of its oscillation as shown in FIGURE 6. As the direction of movement of displacer **20** reverses, the gas is recycled through the heater-regenerator-cooler in that order and the temperature-pressure relationship of the gas decreases and there is no gas flow through conduits **8** and **10** as shown in FIGURE 7. As motion of displacer **20** continues in a counter-clockwise direction the temperature-volume relationship of the gas continues to decrease and gas begins to flow into chamber **6** through conduit **8** to maintain relatively constant pressure as shown in FIGURE 8. Movement of displacer **20** continues until the position shown in FIGURE 3 is obtained and the cycle is repeated in like fashion.

When using helium, suitable operating temperatures for heating means **24** are from about 850° to 1450° F. In use such heater temperatures have provided maximum average gas temperatures of from about 700° to 1300° F. Suitable operating temperatures for cooling means **22** are from about 60° to 150° F. resulting in minimum average gas temperatures of from about 110° to 200° F.

Displacer frequencies of from about 15 to 100 cycles per minute are suitable for operation of the compressor of my invention. Preferred frequencies are from about 30 to 75 cycles per minute.

A pressure responsive member may be positioned between the gas contained in compressor **1** and an external pneumatic system. Such a configuration affords a great advantage by permitting use of a gas such a helium possessing advantageous properties in the heat-actuated regenerative compressor and a different gas possessing advantageous properties for use in any cycling function. For example, a cooling system according to my invention may use helium as a gas in the heat actuated regenerative compressor which serves to drive an efficient refrigerant through a cooling cycle. Refrigerants well known in the art may be utilized. Preferred refrigerants include halogenated hydrocarbons such as Freons.

FIGURE 10 shows one embodiment of my invention wherein compressor **1** has a pressure responsive flexible membrane **28** attached to inner shell casing **5** and positioned between the gas contained in chamber **6** and a second gas or fluid contained in chamber **32**. Operation of compressor **1** causes flexible membrane **28** to pulsate between the full line and dotted line position. Check valve **30** permits entry of gas or fluid to chamber **32**, while check valve **34** permits exit of gas or fluid from chamber **32**. Flexing of membrane **28** toward the dotted line position increases the pressure in chamber **32** causing check valve **34** to open allowing the exit of gas or fluid from chamber **32**. Similarly, as membrane **28** flexes toward the full line position, the pressure in chamber **32** decreases causing check valve **30** to open and permit flow of gas or fluid into chamber **32**. Cycling of such steps produces a pumping action through chamber **32**. Such pumping action effectively drives a refrigerant through a cooling cycle. The flexible pressure responsive means shown in FIGURE 10 as a membrane may take other configurations such as a bellows.

It is sometimes advantageous to have a pneumatic fluid pressure responsive means interspaced between the gas of the heat-actuated regenerative compressor and the system for which the compressor is providing work energy. One advantage of a mechanical translating system in such an application is that the return action may be assisted by various means. Return action assistance permits an independent choice of absolute pressures in the driven associated system and in the driving heat-actuated regenerative compressor.

FIGURE 11 shows one embodiment of a cooling system according to this invention having a mechanical energy translator spaced between the compressor **1** and refrigeration system **48**. In this embodiment, pressure responsive member **36** is a roll-sock seal mounted in a gas and fluid-tight fashion across the end of cylinder **38**. Piston **40** is disposed in a fluid-tight relation within cylinder **38** and extends into chamber **32**, furnishing reciprocal movement between the full line and dotted line positions. An incompressible fluid is contained in chamber **44** of cylinder **38** between piston head **42** and flexible member **36**. The opposite end **46** of piston **40** is adapted for reciprocal movement within chamber **32** which provides a pumping action in the similar fashion as described above for chamber **32** and FIGURE 10. Piston **40** may be returned by any of several means known in the art such as mechanical means as spring **37**, or pneumatic means such as a pressure accumulator bag. The pump formed by piston **40**, chamber **32** and check valves **30** and **34** provides the driving force for movement of a refrigerant in refrigeration system **48** comprising condenser means **50**, fluid motor or expansion valve means **52** and evaporator **54**. The embodiment shown in FIGURE 11 may also be applied for a prime mover system. The pump formed by piston **40**, chamber **32** and check valves **30** and **34** provides the driving force for pumping an incompressible fluid through a hydraulic power generating system serving as a prime mover. Viewing FIGURE 11, such a hydraulic power generating system may be envisioned by **50** and **54** serving as oil accumulation means, and **52** as a fluid motor.

According to this invention, a refrigeration system is provided whereby a heat-actuated regenerative compressor may be efficiently operated using a gas which possesses most desirable physical properties for such use. The working gas of the heat-actuated regenerative compressor is isolated from any other gas or fluid which utilizes work output of the compressor. Therefore, it is possible to utilize a second gas, having optimal properties as a refrigerant, in a cooling system driven by work output from the heat-actuated regenerative compressor.

FIGURE 9 shows the thermodynamic curves for a cooling system according to this invention. Both the power cycle and the cooling cycle are shown in the same temperature-entropy diagram although different gases may be used. Different absolute pressures may be used in the power cycle and the cooling cycle, preferably higher absolute pressures in the power cycle than in the cooling cycle. The power cycle is shown wherein position A corresponds with the physical configuration shown in FIGURE 3. The increase in temperature at constant volume between points A and B is illustrated by the configuration shown in FIGURE 4. Further heating at constant pressure from points B to C is shown by configuration in FIGURE 5, and the mid-point of the power cycle shown at point C corresponds to the physical configuration shown in FIGURE 6. Cooling at constant volume between points C and D corresponds to the configuration shown in FIGURE 7. Further cooling at constant pressure between points D and A is illustrated by the configuration in FIGURE 8. The difference between the solid lines of the power cycle and the dotted constant pressure lines shows the total pressure drop of the system, no more than about

1 p.s.i. at each of the lower and upper pressures. The cooling cycle illustrates a standard Freon cooling cycle.

The overall coefficient of performance of from about 1.0 to 1.3 can be achieved using the cooling system of this invention. These coefficients of performance have been calculated using natural gas as a heat source for the power cycle and Freon as the refrigerant, and represent the overall efficiency from the natural fuel to the cooling output.

The heat-actuated regenerative compressor of my invention may be coupled in series with other similar units to produce greater pressure differentials between overall extremes.

While in the foregoing specification this invention has been described in relation to certain preferred embodiments thereof, and many details have been set forth for purpose of illustration, it will be apparent to those skilled in the art that the invention is susceptible to additional embodiments and that certain of the details described herein can be varied considerably without departing from the basic principles of the invention.

I claim:

1. A heat-actuated regenerative compressor comprising a casing defining a generally cylindrical chamber for confining gas, a heating means positioned within said chamber extending from said casing toward the center of said chamber and extending substantially the length of said chamber, a cooling means positioned within said chamber extending from said casing toward the center of said chamber and extending substantially the length of said chamber, a heat regenerating means juxtaposed to said heating means and said cooling means, an oscillating displacer dividing said chamber into a first and a second volume and by oscillatory movement displacing said gas from said first volume through said heating means, regenerating means and cooling means into said second volume at a higher average temperature-pressure relationship, and from said second volume through said heating means, regenerating means and cooling means into said first volume at a lower average temperature-pressure relationship, and a pressure responsive member in said casing providing for expansion and contraction of said gas for operation of said compressor between fixed pressures.

2. The compressor of claim **1** wherein said gas is an inert gas.

3. The compressor of claim **1** wherein said gas is helium.

4. The compressor of claim **1** wherein said gas is helium and the temperatures of said heating means are from about 850° to 1450° F.

5. The compressor of claim **4** wherein the temperature of said cooling means is from about 60° to 150° F.

6. The compressor of claim **1** wherein said displacer oscillates at from about 15 to 100 cycles per minute.

7. The compressor of claim **1** wherein said displacer oscillates at from about 30 to 75 cycles per minute.

8. The compressor of claim **1** wherein said pressure responsive member is a flexible membrane in said casing.

9. The compressor of claim **1** wherein said pressure responsive member separates said gas from a pneumatic fluid pressure responsive means which translates said expansion and contraction into mechanical energy.

10. The compressor of claim **1** wherein said heating means is supplied with heat obtained by combustion of natural fuels.

11. The compressor of claim **10** wherein said heat is supplied by combustion of natural gas.

12. The compressor of claim **10** wherein said heat is supplied by electricity.

13. A cooling apparatus comprising a heat-actuated regenerative compressor comprising a casing defining a generally cylindrical chamber for confining gas, a heating means positioned within said chamber extending from said casing toward the center of said chamber and extending substantially the length of said chamber, a cooling means positioned within said chamber extending from said casing toward the center of said chamber and extending substantially the length of said chamber, a heat-regenerating means juxtaposed to said heating means and said cooling means, an oscillating displacer dividing said chamber into a first and a second volume and by oscillatory movement displacing said gas from said first volume through said heating means, regenerating means and cooling means into said second volume at a higher average temperature-pressure relationship, and from said second volume through said heating means, regenerating means and cooling means into said first volume at a lower average temperature-pressure relationship, and a pressure responsive member in said casing providing for expansion and contraction of said gas for operation of said compressor between fixed pressures, in combination with a cooling mechanism comprising a condenser means, an expansion means, an evaporation means and a compression means and contained refrigerant wherein said compression means is actuated by expansion and contraction of said pressure responsive member.

14. The cooling apparatus of claim **13** wherein said gas is helium and said refrigerant is a halogenated hydrocarbon.

15. The cooling apparatus of claim **13** wherein said

compression means comprises a mechanical energy translator spaced between said pressure responsive member and said cooling mechanism.

16. The cooling apparatus of claim **15** whereby said energy translator comprises a piston disposed in a fluid-tight relation with a cylinder, the first end of said piston in contact with an incompressible fluid contained in the first end of said cylinder between said first end of said piston and said pressure responsive member, the opposite second end of said piston in the second opposite end of said cylinder; said piston driving said refrigerant through said cooling mechanism by reciprocating action.

17. The cooling apparatus of claim **16** wherein said piston is returned into said first end of said cylinder by a return means.

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MEYER PERLIN, Primary Examiner

U.S. Cl. X.R.

60—59; 62—6