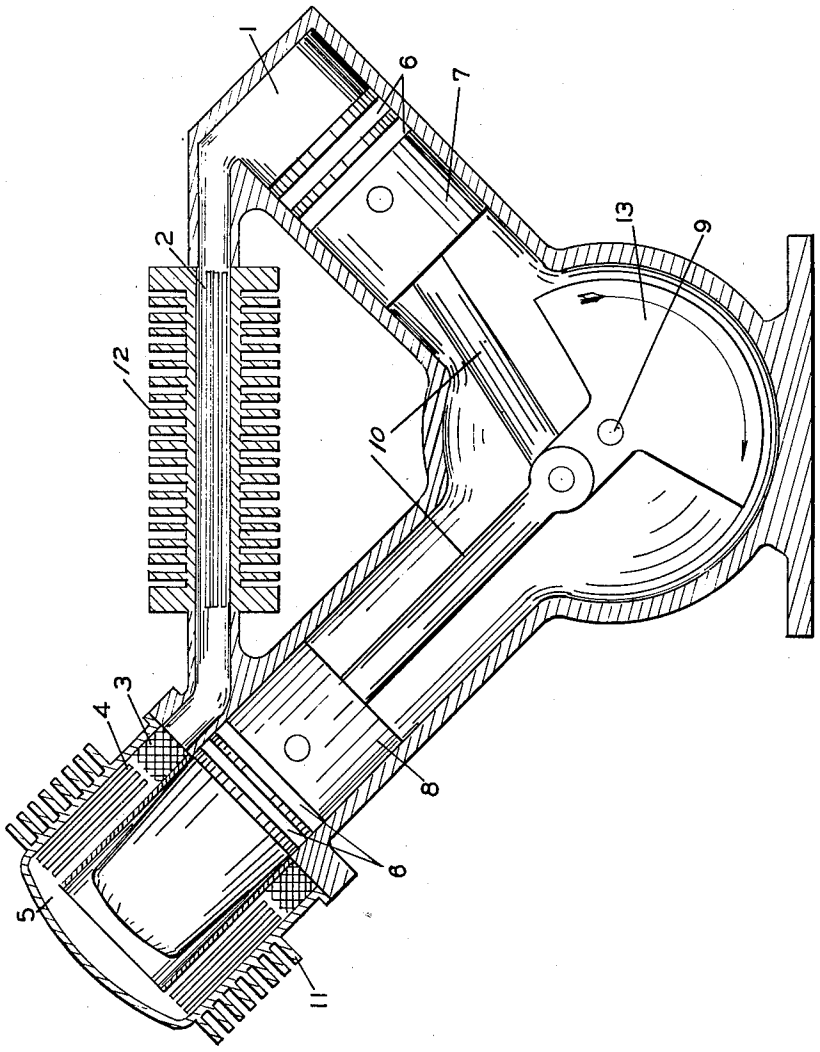
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HOT-GAS ENGINE OR REFRIGERATOR

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HOT-GAS ENGINE OR REFRIGERATOR

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This invention relates to hot-gas apparatus and more particularly, apparatus operating on a closed thermodynamic cycle.

The term hot-gas apparatus operating on a closed thermodynamic cycle includes hot-gas engines in which an external source of heat at a high temperature is applied to the gaseous working medium, and the energy so applied is converted into mechanical energy, as well as refrigerators operating on the reverse hot-gas principle and in which mechanical energy is applied to compress the gaseous working medium and in its subsequent expansion, the working medium produces a refrigerating effect. A discussion of the fundamentals of the hot-gas thermodynamic cycle as it applies to engines and refrigerators is found in the publication "Philips Technical Review," volume 8, No. 5, pages 129 to 136, May 1946.

Hot-gas apparatus comprising a hot chamber, a heater, a regenerator, a cooler and a cold chamber through which the gaseous working medium passes, are known. A hot-gas engine comprising these components is shown in British Patent No. 146,620 to T. A. Rees whereas a refrigerating machine operating on the reverse hot-gas principle and comprising these components is shown in U. S. Patent No. 1,240,862, to I. Lundgaard.

Notwithstanding the fact that hot-gas apparatus has been known for some time, this type of apparatus has not come into general use, because of the shortcomings of the prior devices. More particularly, the prior hot-gas engines have been characterized by a slow speed, a high weight to power ratio, a small power output, poor starting and running characteristics and a low operating efficiency. Prior refrigeration machines operating on the reverse hot-gas engine principle have similarly been unsatisfactory, because of their large bulk, poor operating efficiency, and the limited temperature changes produced.

An object of this invention is to provide a hot-gas apparatus having a high overall operating efficiency.

Another object of this invention is to provide a hot-gas engine which is capable of speeds up to 2000 R. P. M. and higher.

A further object is to provide a hot-gas engine that is relatively quiet in operation, simple in structure, and which has low operating and maintenance costs, good starting and running characteristics, and a low ratio of weight to horsepower.

Still another object of the invention is to provide a refrigeration machine which is compact

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and produces large temperature changes at good efficiency.

These and further objects of the invention will appear as the specification progresses.

In accordance with the invention, the foregoing objects are achieved and the shortcomings of prior hot-gas apparatus are overcome by a specific correlation of the characteristics of the aforementioned five components of the hot-gas apparatus. More particularly, and in accordance with the invention, it has been found that the hot chamber, heater, regenerator, cooler and cold chamber must be arranged in the order named and must be interrelated in form and characteristics in a specific cooperative manner set forth below.

The hot and cold chamber must undergo volume variations from substantially zero to a given value during the complete hot-gas cycle.

The heater element which serves to add heat to the working medium is of the surface contact type and is so arranged that the working medium passes therethrough in a subdivided manner which comprises at least five separate paths. At full load of the apparatus, the critical ranges of the operating characteristics of the heater shall be: (*a*) heat transfer ratio between .2 and .75, preferably between about .35 and .45; (*b*) quality coefficient between about 0.1 and 0.6.

The regenerator element, wherein heat is alternately removed from and added to the working medium, shall have at full load a critical range of operating characteristics as follows: (*a*) heat transfer ratio between .9 and 1.0; (*b*) quality coefficient between 0.05 and 0.6; (*c*) heat capacity at least two and one-half times the heat capacity of the gas that flows through the regenerator in one direction during one cycle.

The cooler which serves to remove heat from the working medium is of the contact type, and is so arranged that the working medium passes therethrough in a subdivided manner, which comprises at least five separate paths. At full load, the critical ranges of the operating characteristics shall be: (*a*) heat transfer ratio between .2 and .75, preferably between about .35 and .45; (*b*) quality coefficient between 0.1 and 0.6.

The total volume of voids in the heater, regenerator and cooler shall be between 0.5 and 3 times, preferably between about 0.75 and 1 times the maximum volume of the hot space.

The volume variations in the hot chamber and the cold chamber must have a phase difference between 60° and 120°.

The heat transfer ratio and quality coefficients

set forth above, are based on the ratio of heat transfer rate to pressure drop, and these factors for each element may be determined by means of the following formulas:

(1) $$\Lambda=\frac{\alpha\varphi}{\omega}$$

(2) $$E\mu=\frac{\Delta\rho}{\frac{1}{2}\frac{\rho^2v^2}{\bar{\rho}}}$$

(3) $$\text{heat transfer ratio}=\frac{\Lambda}{\Lambda+2}$$

(4) $$\text{quality coefficient}=\frac{\Lambda}{E\mu}$$

wherein:

Λ=heat transfer number
$E\mu$=pressure drop number (Euler's number)
α=heat transfer coefficient
φ=total area of heat exchange surface
ω=heat capacity of the amount of medium flowing through per unit time
ρ=density of the work medium measured at a given cross-section in the considered heat transfer element.
v=mean velocity of the work medium measured at the same point as for (ρ and v can be measured at any point in the considered heat transfer element since the product of $\rho\times v$ is constant)
$\bar{\rho}$=mean of the densities of the work medium at the entrance and exit cross-sections of the considered heat transfer element.
$\Delta\rho$=pressure drop across the heat transfer element.

In addition to the foregoing five elements, arranged and correlated in the specific manner outlined, the hot-gas apparatus according to the invention comprises a gaseous fluid such as air, nitrogen, hydrogen, helium and the like which serves as a working medium and is enclosed within the apparatus and arranged to traverse the elements in the order given during the first part of the cycle, and retraverse the elements in a reversed sequence during the second part of the cycle. Piston means are provided whereby the working medium is substantially compressed in the cold chamber and substantially expanded in the hot chamber, the maximum volume of the hot chamber being approximately ninety degrees ahead in phase to the maximum volume in the cold chamber. Heat is added to the working medium by the heater and is removed by the cooler, the regenerator serving as a heat reservoir, whereby a given amount of heat is added to the medium as it moves from the cold chamber to the hot chamber, an equivalent amount of heat being removed by the regenerator from the medium as it is returning from the hot chamber to the cold chamber. A link means is associated with the piston means so that by piston action the working medium is made to conform to a predetermined thermodynamic cycle whereby mechanical energy is realized from the heat energy added to the working medium.

The heater and cooler of the hot-gas device of the invention are characterized in that the work medium passes in a subdivided manner, preferably through slots, which are extremely narrow, in fact much narrower than would normally be considered for heat transfer apparatus of this type. While the pressure drop through the heater and cooler increases as the slot width is narrowed, by means of the formulas developed and

the critical limits, both of which distinguish the invention, it is relatively easy to establish the minimum slot width.

The sole figure of the drawing illustrates a schematic cross-sectional view of a two-cylinder V-type hot-gas engine in which are embodied the principles of applicant's invention.

In the drawing, numeral 1 indicates a cold chamber wherein the working medium is substantially compressed after which it is passed through a cooler 2, which removes the heat of compression from the medium, the medium then being passed through a regenerator 3, which adds heat to the working medium, after which the working medium passes through a heater 4, which further increases the temperature of the medium, the medium finally being directed into a hot chamber 5, in which substantial expansion of the medium takes place. The first half of the thermodynamic cycle of the hot-gas engine is completed in the five elements in the sequence as outlined above. The second half of the cycle occurs in the reverse order, viz., the medium successively passing from the hot chamber 5, to heater 4, then to the regenerator 3, through the cooler 2, and finally to the cold chamber 1.

The five elements are maintained in open communication with each other. The cold and hot chambers are further formed in part by a cold piston 7 and a hot piston 8, respectively, both pistons having substantially a zero minimum clearance, each of the pistons having sealing members 6 for the prevention of blow-by or escape of the medium from the work chambers. Such a cycle is called a "closed cycle;" substantially the same medium being repeatedly used in successive cycles. In practice, it is impossible to prevent a small quantity of medium from escaping from the cycle, and make-up means (not shown) are generally employed to offset any such loss of medium.

The pistons are arranged to be driven by the working medium as it passes from one end of the cycle to the other, and are coupled to a drive shaft 9, by connecting rods 10. A fly-wheel 13 is coupled to the drive shaft as shown. The pistons are further arranged to cause a phase difference between the volume variations of the hot chamber and the volume variations of the cold chamber, maximum volume of the hot chamber being approximately 90° ahead of phase with maximum volume of the cold chamber.

The regenerator 3 is most conveniently made in the form of a filamentary metallic mass having high heat transfer characteristics. Copending application No. 767,305, filed August 7, 1947, now Patent No. 2,564,100, sets forth in great detail the structure and characteristics of a regenerator for use with a hot-gas engine of the type under consideration herein. Basically, such a regenerator comprises a filamentary metallic mass which is uniformly distributed through a portion of the regenerator space and has a surface area per unit volume of the space occupied, preferably between 100 cm.^{2}/cm.^{3} and 200 cm.^{2}/cm.^{3} The mass of the filamentary material has a thickness in the direction of flow of the working medium, preferably between about 0.8 cm. and 4 cm., a heat capacity between about two and one-half to twenty-five times the heat capacity of the working medium flowing through the regenerator during one stroke of the engine, and a total volume of voids, preferably less than about three times the mean volume

of the working medium passing through the regenerator in one direction during each cycle. In addition, the regenerator has a space factor, preferably between 6 to 25. By the expression "heat capacity" is meant the quantity of heat needed to increase the temperature of the filling mass 1° centigrade. The expression "space factor" means the ratio between the overall volume occupied by the regenerator to the volume occupied by the filamentary material of the regenerator.

The cooler **2** as well as the heater **4** consists of a series of sub-dividing channel members arranged to facilitate a rapid heat transference. A burner system, not shown, surrounds the heater, and heat is conducted to the heater by means of fins **11**. A cooling system, not shown, surrounds the cooler, and heat is conducted away from the cooler by means of fins **12**. The cooling system can be either air or liquid type.

From the foregoing, it will be apparent that by embodying specific elements in a definite interrelation in a hot-gas device, there has been provided a novel hot-gas device having improved characteristics and advantages not realized by prior devices. More particularly, hot-gas engines, according to the invention, are characterized by an overall operating efficiency of the order of 10 to 25%, running speeds up to 2000 R. P. M. and higher, and a weight to horsepower ratio comparable to that found in the commercial types of internal combustion engines. The hot-gas engine of the invention is relatively quiet in operation, and has low operating cost since most of the lower cost fuels can be used. These factors plus the simplicity of structure and the high degree of reliability which are characteristic of the improved hot-gas engine, make this engine a prime mover of unusual merit.

Among the points of novelty featured in this invention, it is to be noted that the heater, regenerator and cooler conform to carefully chosen limits of efficiency, quality coefficient and volume, the extreme importance of which has not been recognized before in the hot-gas engine art.

While the invention has been described with respect to a hot-gas engine used as a prime mover, the principles of the invention are equally applicable to a refrigerating apparatus of similar construction and operated according to the reverse hot-gas engine principle. Furthermore, it is apparent that modifications can be made in structure without departing from the spirit of the invention.

What I claim is:

1. A closed cycle hot-gas apparatus having elements comprising means defining a hot chamber, means defining a cold chamber, a regenerator having a heat transfer ratio of between .9 and 1.0, a quality coefficient of between 0.05 and 0.6 and a heat capacity at least about two and one-half times the heat capacity of the work medium flowing therethrough in one direction during one cycle, a heater interposed between the hot chamber and the regenerator and having a heat transfer ratio of between .2 and .75 and a quality coefficient of between 0.1 and 0.6, and a cooler interposed between the cold chamber and the regenerator, said cooler having a heat transfer ratio of between .2 and .75 and a quality coefficient of between 0.1 and 0.6, each of said elements being arranged in open communication with the adjacent element.

2. A closed cycle hot-gas apparatus having elements comprising means defining a hot chamber, means defining a cold chamber, a regenerator having a heat transfer ratio of between .9 and 1.0, a quality coefficient of between 0.05 and 0.6 and a heat capacity at least about two and one-half times the heat capacity of the work medium flowing therethrough in one direction during one cycle, a heater interposed between the hot chamber and the regenerator and having a heat transfer ratio of between .35 and .45 and a quality coefficient of between 0.1 and 0.6, and a cooler interposed between the cold chamber and the regenerator, said cooler having a heat transfer ratio of between .35 and .45 and a quality coefficient of between 0.1 and 0.6, each of said elements being arranged in open communication with the adjacent element.

3. A closed cycle hot-gas apparatus having elements comprising means defining a hot chamber, means defining a cold chamber, a regenerator having a heat transfer ratio of between .9 and 1.0, a quality coefficient of between 0.05 and 0.6 and a heat capacity at least about two and one-half times the heat capacity of the work medium flowing therethrough in one direction during one cycle, a heater interposed between the hot chamber and the regenerator and having a heat transfer ratio of between .2 and .75 and a quality coefficient of between 0.1 and 0.6, and a cooler interposed between the cold chamber and the regenerator, said cooler having a heat transfer ratio of between .20 and .75 and a quality coefficient of between 0.1 and 0.6, each of said elements being arranged in open communication with the adjacent element, the total volume of voids in the heater, regenerator and cooler being between about 0.5 and about 3.0 times the maximum volume of the hot chamber.

4. A closed cycle hot-gas apparatus having elements comprising means defining a hot chamber, means defining a cold chamber, a regenerator having a heat transfer ratio of between .9 and 1.0, a quality coefficient of between 0.05 and 0.6 and a heat capacity at least about two and one-half times the heat capacity of the work medium flowing therethrough in one direction during one cycle, a heater interposed between the hot chamber and the regenerator and having a heat transfer ratio of between .35 and .45 and a quality coefficient of between 0.1 and 0.6, and a cooler interposed between the cold chamber and the regenerator, said cooler having a heat transfer ratio of between .35 and .45 and a quality coefficient of between 0.1 and 0.6, each of said elements being arranged in open communication with the adjacent element, the total volume of voids in the heater, regenerator and cooler being between about .75 and about 1.0 times the maximum volume of the hot chamber.

5. A closed cycle hot-gas apparatus having elements comprising means defining a hot chamber, means defining a cold chamber, said hot chamber defining means and said cold chamber defining means being so arranged to produce volume variations in said hot and cold chambers having a phase difference between 60° and 120°, the minimum volume of said hot chamber and said cold chamber being substantially zero as determined by constructional clearances of said chamber defining means, a regenerator having a heat transfer ratio of between .9 and 1.0, a quality coefficient of between 0.05 and 0.6 and a heat capacity at least about two and one-half times the heat capacity of the work medium flowing

therethrough in one direction during one cycle, a heater interposed between the hot chamber and the regenerator and having a heat transfer ratio of between .2 and .75 and a quality coefficient of between 0.1 and 0.6, and a cooler interposed between the cold chamber and the regenerator, said cooler having a heat transfer ratio of between .2 and .75 and a quality coefficient of between 0.1 and 0.6, each of said elements being arranged in open communication with the adjacent element, the total volume of voids in the heater, regenerator and cooler being between about 0.5 and about 3.0 times the maximum volume of the hot chamber.

6. A closed cycle hot-gas apparatus having elements comprising means defining a hot chamber, means defining a cold chamber, the minimum volume of said hot chamber and said cold chamber being substantially zero as determined by constructional clearances of said chamber defining means, a regenerator having a heat transfer ratio of between .9 and 1.0, a quality coefficient of between 0.05 and 0.6 and a heat capacity at least about two and one-half times the heat capacity of the work medium flowing therethrough in one direction during one cycle, a heater interposed between the hot chamber and the regenerator and having a heat transfer ratio of between .35 and .45 and a quality coefficient of between 0.1 and 0.6, and a cooler interposed between the cold chamber and the regenerator, said cooler having a heat transfer ratio of between .35 and .45 and a quality coefficient of between 0.1 and 0.6, each of said elements being arranged in open communication with the adjacent element, the total volume of voids in the heater, regenerator and cooler being between about .75 and about 1.0 times the maximum volume of the hot chamber.

7. A closed cycle hot-gas apparatus having elements comprising means defining a hot chamber, means defining a cold chamber, the minimum volume of said hot chamber and said cold chamber being substantially zero as determined by constructional clearances of said chamber defining means, said hot chamber and cold chamber defining means being so arranged that the volume variations in said chambers are out of phase with each other by approximately ninety degrees, a regenerator having a heat transfer ratio of between .9 and 1.0, a quality coefficient of between 0.05 and 0.6 and a heat capacity at least about two and one-half times the heat capacity of the work medium flowing therethrough in one direction during one cycle, a heater interposed between the hot chamber and the regenerator and having a heat transfer ratio of between .2 and .75 and a quality coefficient of between 0.1 and 0.6, and a cooler interposed between the cold chamber and the regenerator, said cooler having a heat transfer ratio of between .2 and .75 and a quality coefficient of between 0.1 and 0.6, each of said elements being arranged in open communication with the adjacent element, the total volume of voids in the heater, regenerator and cooler being between about 0.5 and about 3.0 times the maximum volume of the hot chamber.

8. A closed cycle hot-gas apparatus having elements comprising means defining a hot chamber, means defining a cold chamber, the minimum volume of said hot chamber and said cold chamber being substantially zero as determined by constructional clearances of said chamber defining means, said hot chamber and cold chamber defining means being so arranged that the volume variations in said chambers are out of phase with each other by approximately ninety degrees, a regenerator having a heat transfer ratio of between .9 and 1.0, a quality coefficient of between 0.05 and 0.6 and a heat capacity at least two and one-half times the heat capacity of the work medium flowing therethrough in one direction during one cycle, a heater interposed between the hot chamber and the regenerator and having a heat transfer ratio of between .2 and .75 and a quality coefficient of between 0.1 and 0.6, a cylinder portion on each side of said heater being of reduced thickness, and a cooler interposed between the cold chamber and the regenerator, said cooler having a heat transfer ratio of between .2 and .75 and a quality coefficient of between 0.1 and 0.6, each of said elements being arranged in open communication with the adjacent element, the total volume of voids in the heater, regenerator and cooler being between about 0.5 and about 3.0 times the maximum volume of the hot chamber.

9. A closed cycle hot-gas apparatus having elements comprising means defining a hot chamber, means defining a cold chamber, the minimum volume of said hot chamber and said cold chamber being substantially zero as determined by constructional clearances of said chamber defining means, said hot chamber and cold chamber defining means being so arranged that the volume variations in said chambers are out of phase with each other by approximately ninety degrees, a regenerator having a heat transfer ratio of between .9 and 1.0, a quality coefficient of between 0.05 and 0.6 and a heat capacity at least two and one-half times the heat capacity of the work medium flowing therethrough in one direction during one cycle, a heater having at least five separate flow paths for the work medium interposed between the hot chamber and the regenerator and having a heat transfer ratio of between .35 and .45 and a quality coefficient of between 0.1 and 0.6, a cylinder portion on each side of said heater being of reduced thickness, and a cooler having at least five separate flow paths for the work medium interposed between the cold chamber and the regenerator, said cooler having a heat transfer ratio of between .35 and .45 and a quality coefficient of between 0.1 and 0.6, each of said elements being arranged in open communication with the adjacent element, the total volume of voids in the heater, regenerator and cooler being between .75 and 1.0 times the maximum volume of the hot chamber.

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