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HOT-GAS RECIPROCATING APPARATUS
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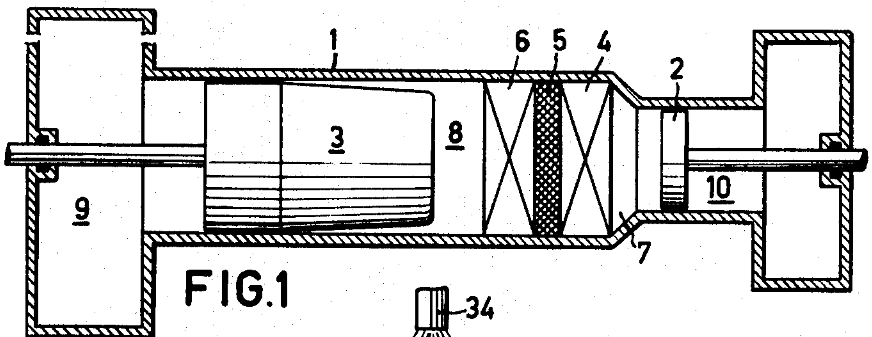

FIG.1

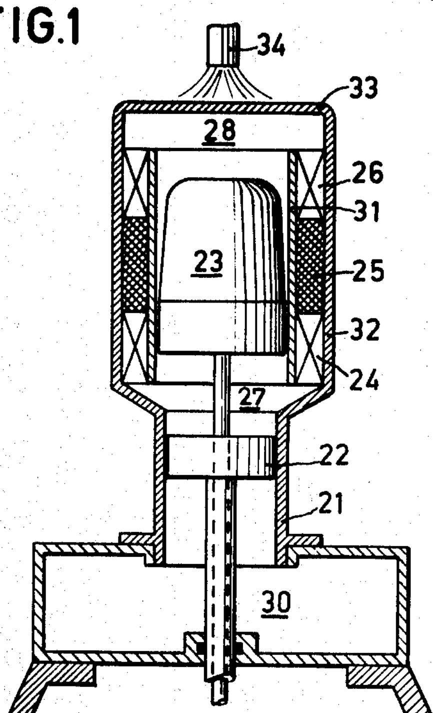

FIG.2

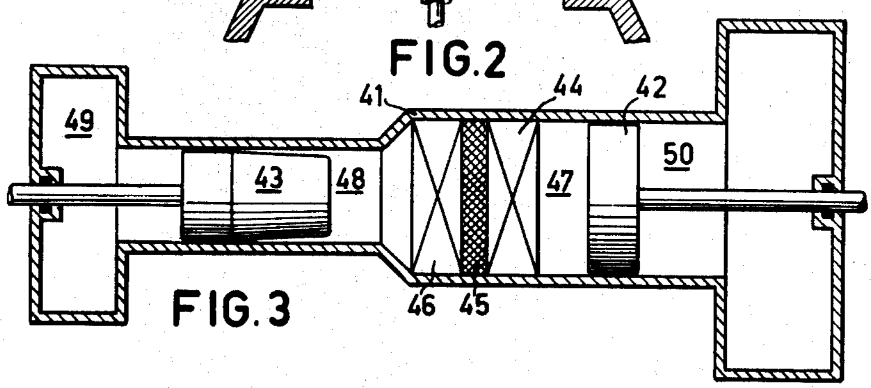

FIG.3

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HOT-GAS RECIPROCATING APPARATUS

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The invention relates to a hot-gas reciprocating apparatus provided with one or more cylinder spaces, in each of which two piston-shaped members are adapted to reciprocate out of phase and are capable of varying the volume of an expansion space and a compression space. The said spaces communicate with one another and in the operation of the apparatus have different mean temperatures, the means of communication between the said spaces including one or more regenerators through which a medium can flow between the said two spaces, while the apparatus is provided with a device for controlling the power, which control is based upon a change in the phase relationship between the movements of the two piston-shaped members.

A known method of regulating the power of hot-gas reciprocating apparatus is based upon changes in the pressure level of the working medium. In this method, a rapid fall of the extracted power can be compensated for by the so-called short-circuit control, which is based on the phase shift of the pressure, which shift is produced by establishing a communication between the working space of a cylinder and either a buffer space or one or more working spaces of other cylinders.

This regulating method, however, has a limitation in that the rate of regulating depends upon the time required to supply the desired amount.

In hot-gas reciprocating apparatus of the type to which the invention relates, the disadvantages of the said method of regulation are overcome by the use of the so-called phase regulation. In this method of regulation, the amount of medium in the working space remains constant.

This phase regulation is based upon a change in the phase relationship between the piston movements, in apparatus of the displacer type on the change in the phase relationship between the movements of the piston and the displacer. This phase regulation, however, has a limitation in that, if the values of the variations of the compression space and the expansion space are equal, a considerable difference between the maximum and minimum pressures produced remains in that regulating position in which the power becomes zero or the direction of rotation of the motor is reversed. This means that a constant means pressure level the forces exerted upon the bearings in starting of reversing remain unacceptably large.

To overcome the said disadvantage, the hot-gas reciprocating apparatus according to the invention is characterized in that with a phase relationship in which the power becomes zero, the volumes of the expansion space and the compression space vary substantially in phase opposition, the values of the variations of the volumes of the expansion space and the compression space being related so that substantially no pressure fluctuations are produced in the cylinder space concerned.

The invention is based on the recognition that a proper choice of the ratio between the swept volumes of the expansion space and the compression space surprisingly enables pressure fluctuations to be entirely avoided in the case of a phase relationship in which the power becomes zero.

2

A favourable embodiment of a hot-gas reciprocating apparatus according to the invention designed as a hot-gas reciprocating engine is characterized in that with a phase relationship in which the volumes of the expansion space and of the compression space vary in phase opposition, the value of the variations in volume of the compression space is less than the value of the variations in volume of the expansion space.

A further favourable embodiment of a hot-gas reciprocating apparatus according to the invention designed as a hot-gas reciprocating engine of the displacer type is characterized in that the ratio between the swept volume of the compression piston and the swept volume of the displacer is substantially equal to the value $1-\tau$, where τ represents the ratio between the absolute compression temperature and the absolute expansion temperature.

A further favourable embodiment of a hot-gas reciprocating apparatus according to the invention designed as a hot-gas reciprocating engine of the two-piston type is characteirzed in that the ratio between the swept volume of the compression piston and the swept volume of the expansion piston is at least substantially equal to the ratio (τ) between the absolute compression temperature and the absolute expansion temperature.

A further favourable embodiment of a hot-gas reciprocating apparatus according to the invention designed as a hot-gas refrigerator is characterized in that with a phase relationship in which the volumes of the expansion space and of the compression space vary in phase opposition, the value of the variations in volume of the compression space exceeds the value of the variation in volume of the expansion space.

A favourable embodiment of a hot-gas reciprocating apparatus according to the invention designed as a cold-gas refrigerator of the two piston type is characterized in that the ratio between the swept volume of the compression piston and the swept volume of the expansion piston is at least substantially equal to the ratio τ between the absolute compression temperature and the absolute expansion temperature.

In order that the invention may readily be carried into effect, reference will now be made, by way of example, to the accompanying diagrammatic drawings, which show embodiments of cylinders of hot-gas reciprocating apparatus with the piston-shaped members adapted to reciprocate therein.

To simplify the description, the means for driving the piston-shaped members are not shown. These means do not fall within the scope of the invention and may be designed in known manner. Driving may be effected mechanically, electrically or hydraulically, while a regulating arrangement is provided which enables the phase relationship between the movements of the piston-shaped members to be changed.

FIGURE 1 is a diagrammatic sectional view of a hot-gas reciprocating engine of the two-piston type.

FIGURE 2 is a diagrammatic sectional view of a hot-gas reciprocating engine of the displacer type.

FIGURE 3 is a diagrammatic sectional view of a cold-gas refrigerator of the two-piston type.

Referring now to FIG. 1, a compression piston **2** and a displacer or an expansion piston **3** are adapted to reciprocate in a cylinder **1**. Between the said two pistons, the cylinder **1** contains a cooler **4**, a regenerator **5** and a heater **6**. In the operation of the apparatus, the compression piston **2** and the displacer piston **3** reciprocate with a mutual phase difference such that the working medium contained in the cylinder **1** between the said two pistons is compressed when it is mainly contained in a cold compression space **7**, and expanded when it is mainly contained in a hot expansion space **8**. Between the expansion period and the compression period the medium is transferred through the cooler **4**, the regenerator **5** and the heater **6** from the compression space to the expansion space and vice versa. The cooler **4** may be a water-cooler. Heat is supplied to the heater **6**, for example, with the aid of a burner or of a medium having a higher temperature. Buffer spaces **9** and **10** are located at the sides of the displacer piston **3** and the compression piston **2**, respectively, more remote from the working space. The mean pressure in these buffer spaces is equal to the mean pressure in the working space. The variation of the pressure in the said spaces is kept small by proportioning them sufficiently large.

As the figure shows, the swept volume of the compression piston is smaller than that of the displacer piston, the swept volume of the compression piston being equal to τ times the swept volume of the displacer piston. Here τ is the ratio between the absolute temperature T_c at which compression takes place and the absolute temperature T_e at which expansion takes place. It will be appreciated that in the case of a hot-gas reciprocating engine τ always is less than unity.

If now the power of the engine is controlled by varying the phase relationship between the movements of the compression and displacer pistons, no pressure fluctuations will occur at zero power, that is to say, when the pistons move substantially in phase with one another.

This can be explained as follows. When both pistons move to the right-hand side, the expansion space **8** is reduced by the swept volume V_e of the displacer piston. Assuming the pressure in the working space to remain constant, a volume V_e of gas at a temperature T_e is to be transferred from the expansion space to the compression space **7** through the heater **6**, the regenerator **5** and the cooler **4**.

During this transfer, the gas is cooled to the temperature T_c of the compression space. Thus, an amount of gas having a volume τV_e flows into the compression space. Hence, to maintain the pressure constant, the volume of the compression space must be increased by a volume τV_e. This implies that the swept volume of the compression V_c must be equal to τ times the swept volume V_e of the displacer piston. The hot-gas reciprocating engine of FIG. 1 satisfies this condition, so that at a phase angle equal to bero no pressure fluctuations occur. The above shows that with the phase relationship in which the power output of the engine is zero, the volumes of the expansion space and of the compression space vary in phase opposition. The expansion volume is reduced by V_e while the compression volume is increased by τV_e. The mean pressure prevailing in the working space during this process, is compensated for by the pressure prevailing in the buffer spaces **9** and **10**, so that substantially no additional load is imposed on the bearings.

In the embodiment of FIG. 1, the difference in the swept volumes of the displacer and compression pistons is obtained by the use of different diameters. It will be appreciated that the same effect may be achieved by making the strokes of the said two pistons different.

FIG. 2 is a sectional view of a hot-gas reciprocating apparatus of the displacer type. A compression piston **22** is adapted to reciprocate in a cylinder **21**. A displacer **23** is adapted to reciprocate in a cylinder **31**. An annular channel, which is formed by the outer wall of the cylinder **31** and the inner wall of a jacket **32**, contains a cooler **24**, a regenerator **25** and a heater **26**. Through these elements the working medium may flow from a compression space **27** to an expansion space **28** and vice versa. Below the compression piston is located a buffer space **30**, in which a mean pressure is maintained which is equal to that in the working space. The volume of the buffer space **30** is dimensioned so that substantially no pressure fluctuations occur in it.

To supply the required thermal energy, a burner **34** is directed onto an end face **33** of the motor.

In operation, an absolute temperature T_c of, for example, 300° K. prevails in the compression space and an absolute temperature T_e of, for example, 900° K. prevails in the expansion space. The piston **22** and the displacer **23** may be made to reciprocate with a variable phase difference. By varying this phase difference the output power of the engine is varied. When the piston and the displacer reciprocate substantially in phase, the power is zero. In this situation no pressure fluctuations are produced in the motor of FIG. 2, in which the volume swept by the compression piston **22** is equal to $(1-\tau)$ times the volume swept by the displacer **23**.

This may be explained as follows. When the displacer **23** and the piston **22** are simultaneously moved upwards, the volume of the expansion space **28** is reduced by the volume V_e swept by the displacer. Hence with constant pressure a gas voulme (V_eT_e) is to be transferred to the compression space through the regenerator **25**, in which the gas is cooled to a temperature T_c. When arriving in the compression space, this gas has a volume

$$\frac{T_c}{T_e}V_e=\tau V_e$$

By the upward movement of the displacer **23** the compression space is increased by the swept volume V_e and this volume exceeds by $(1-\tau)V_e$ the gas volume τV_e required to be taken in when the pressure remains constant. To nullify this difference, the volume swept by the compression piston must be $(1-\tau)$ times the volume swept by the displacer. This condition is satisfied by the hot gas reciprocating engine of FIG. 2. This again shows that at the phase relationship at which the output power becomes zero, the volumes of the expansion space and of the compression space vary in phase opposition. In this process, the volume of the expansion space is reduced by V_e while the volume of the compression space is increased by τV_e.

Although in the embodiment of FIG. 2 the difference in the volumes swept by the piston and the displacer is obtained by using different diameters, it will be appreciated that the same object may be achieved by making the strokes of the piston and the displacer different.

FIG. 3 shows an embodiment of a cold-gas refrigerator of the two-piston type. In a cylinder **41** a compression piston **42** and displacer or an expansion piston **43** are adapted to reciproate with a phase difference, the phase relationship between these pistons being variable. Between the said two pistons are disposed a cooler **44**, a regenerator **45** and a freezer **46**, through which elements the working medium may flow between a compression space **47** and a displacer space **48**. At the sides of the expansion piston **43** and the compression piston **42** more remote from the working space are located buffer spaces **49** and **50** respectively, in which a mean pressure equal to that in the working space is maintained. As the figure shows, the diameters of the displacer piston and the compression piston are proportioned so that the volume swept by the displacer piston is τ times the volume swept by the compression piston, where τ is the ratio between the absolute compression temperature of, for example, 300° K. and the absolute expansion temperature of, for example 100° K. As a result, substantially no pressure fluctuations occur in the working space at zero phase difference between the movements of the compression piston and the displacer piston.

This may be explained as follows. When the piston **42** and the displacer **43** are simultaneously moved to the left, the piston displaces a gas volume V_c having a temperature T_c from the compression space **47** to the expansion space **48**. In passing through the regenerator this gas is cooled so that, with constant pressure, a volume

$$\frac{1}{\tau}=V_c$$

enters the expansion space, where

$$\tau = \frac{T_c}{T_e}$$

that is to say, τ exceeds unity. If the pressure in the working space is to remain constant, the volume V_e swept by the displacer piston must be equal to

$$V_e = \frac{1}{\tau} V_c$$

that is to say, the volume V_c swept by the compression piston must be equal to τ times the volume V_e swept by the displacer piston.

The above shows that by taking a step which is comparatively simple from a constructional point of view a hot-gas reciprocating apparatus is obtainable in which no or substantially no pressure fluctuations in the working space are produced in the case of a phase relationship between the movements of the piston-shaped bodies at which the power becomes zero.

It will be appreciated that in some cases in which, when the power is zero, small pressure fluctuations are acceptable, a slight deviation from the above-mentioned ratio between the swept volumes is permissible.

What is claimed is:

1. A hot-gas reciprocating apparatus comprising cylinder means, at least two piston-shaped members adapted to reciprocate therein with a mutual phase difference, said cylinder means and piston-shaped members defining an expansion space and a compression space, a medium in said spaces, said spaces having different mean temperatures, means connecting said spaces including at least one regenerator through which said medium flows, a buffer space adjacent to said compression space and connected to said cylinder means, and a device for regulating the power of said apparatus based on changes in the phase relationship between the movements of said piston-shaped members whereby when said phase relationship is such that said power becomes zero the volumes of the expansion space and compression space vary substantially in phase opposition, the piston-shaped members having such a stroke volume ratio that temperature influences thereon are eliminated whereby no pressure variations will occur in the cylinder means when the power is zero, said piston-shaped members being a compression piston and a displacer respectively, and the ratio between the volume traversed by said compression piston and the volume traversed by said displacer is substantially equal to $1-\tau$ where τ represents the ratio between the absolute compression temperature and the absolute expansion temperature.

2. A hot-gas reciprocating apparatus comprising cylinder means, at least two piston-shaped members adapted to reciprocate therein with a mutual phase difference, said cylinder means and piston-shaped members defining an expansion space and a compression space, a medium in said spaces, said spaces having different mean temperatures, means connecting said spaces including at least one regenerator through which said medium flows, buffer spaces on opposite sides of said piston-shaped members from said expansion space and compression space and connected to said cylinder means, and a device for regulating the power of said apparatus based on changes in the phase relationship between the movements of said piston-shaped members whereby when said phase relationship is such that said power becomes zero the volumes of the expansion space and compression space vary substantially in phase opposition, the piston-shaped members having such a stroke volume ratio that temperature influences thereon are eliminated whereby no pressure variations will occur in the cylinder means when the power is zero, said piston-shaped members being a compression piston and a displacer respectively and the ratio between the volume traversed by the compression piston and the volume traversed by the displacer is substantially equal to the ratio τ between the absolute compression temperature and the absolute expansion temperature.

3. A hot-gas reciprocating apparatus operating as a refrigerator comprising cylinder means, at least two piston-shaped members adapted to reciprocate therein with a mutual phase difference, said cylinder means and piston-shaped members defining an expansion space and a compression space, a medium in said spaces, said spaces having different mean temperatures, means connecting said spaces including at least one regenerator through which said medium flows, buffer spaces on opposite sides of said piston-shaped members from said expansion space and compression space and connected to said cylinder means, and a device for regulating the power of said apparatus based on changes in the phase relationship between the movements of said piston-shaped members whereby when said phase relationship is such that said power becomes zero the volumes of the expansion space and compression space vary substantially in phase opposition, the piston-shaped members having such a stroke volume ratio that temperature influences thereon are eliminated whereby no pressure variations will occur in the cylinder means when the power is zero, said piston-shaped members being a compression piston and a displacer respectively, and the ratio between the volume traversed by said compression piston and the volume traversed by said displacer is substantially equal to the ratio τ between the absolute compression temperature and the absolute expansion temperature.

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