HOT-GAS RECIPROCATING ENGINE

Filed Dec. 28, 1967 4 Sheets-Sheet 1

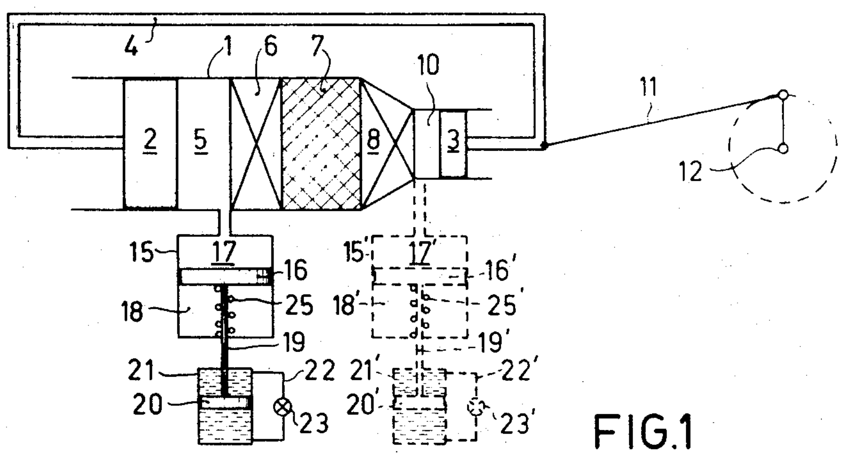

FIG.1

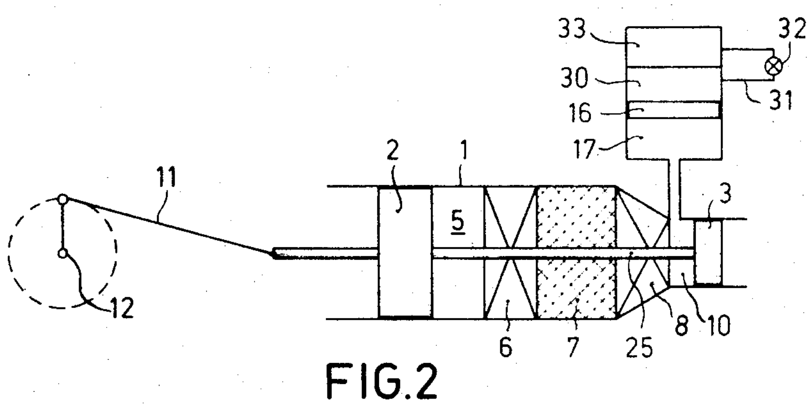

FIG.2

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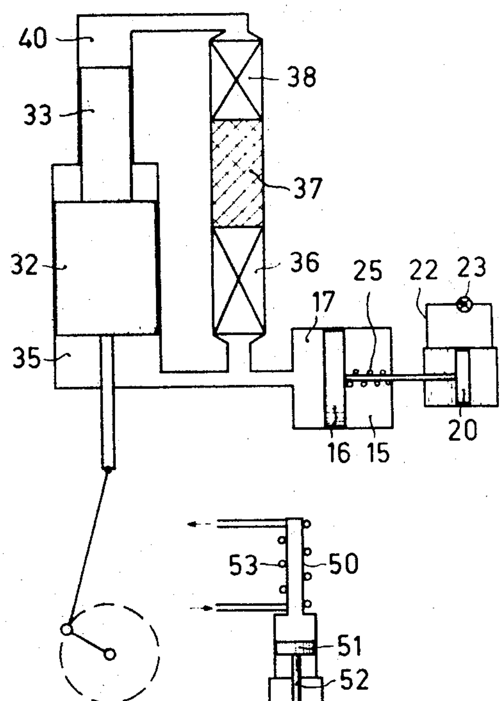

FIG.3

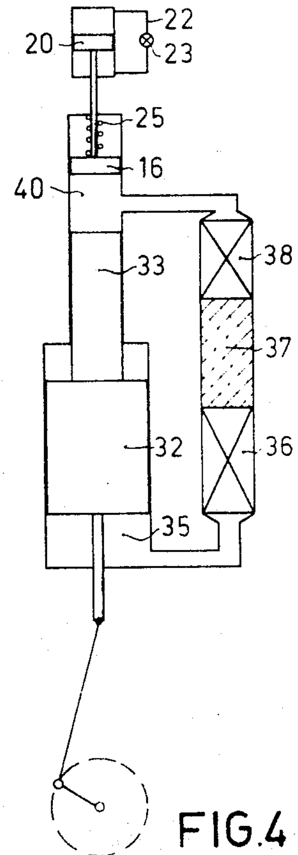

FIG.4

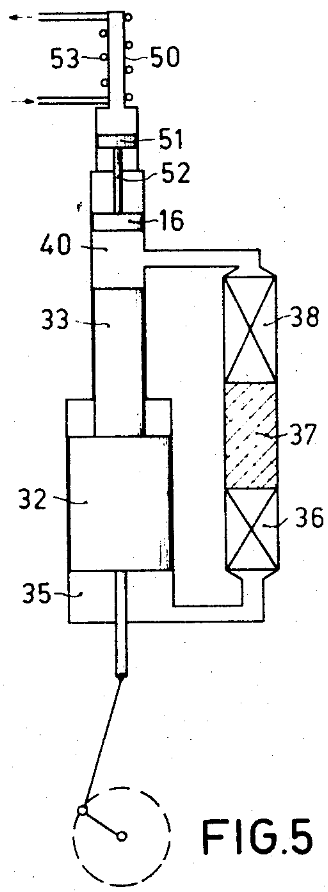

FIG.5

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HOT-GAS RECIPROCATING ENGINE

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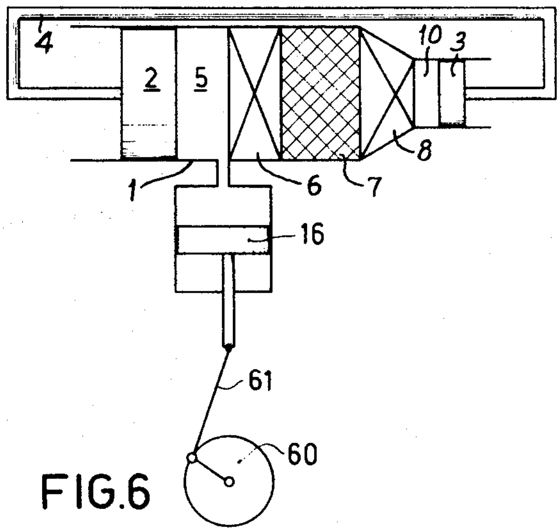

FIG.6

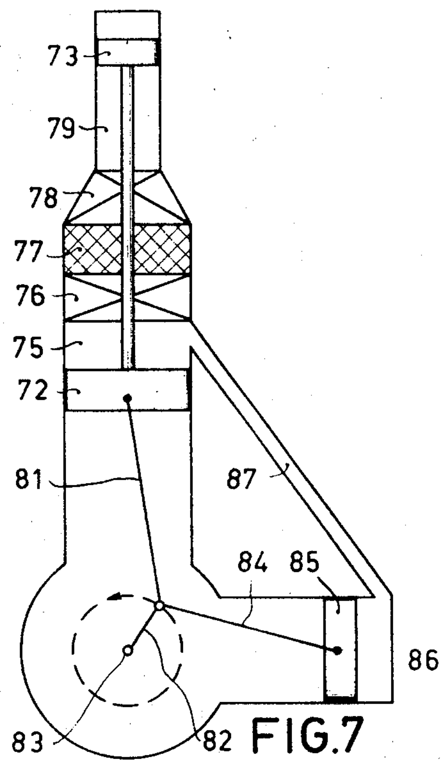

FIG.7

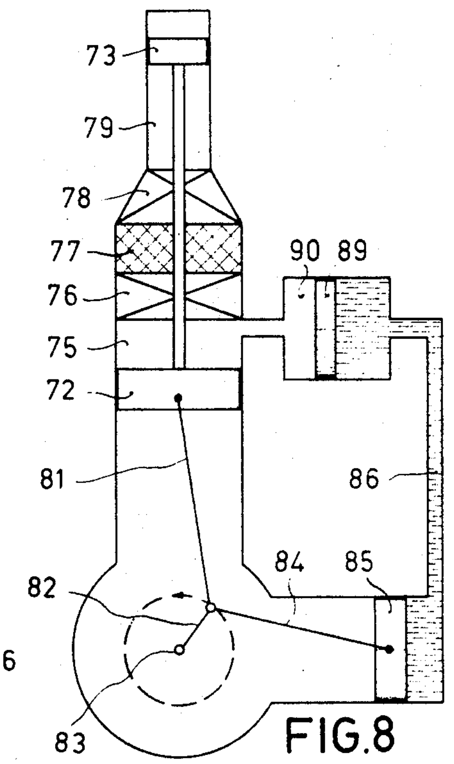

FIG.8

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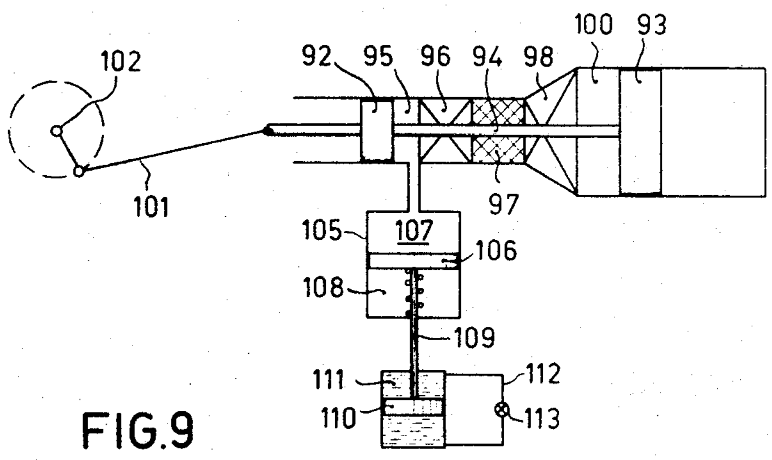

FIG.9

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3,472,037

HOT-GAS RECIPROCATING ENGINE

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Int. Cl. F25b 9/00
U.S. Cl 62—6 13 Claims

ABSTRACT OF THE DISCLOSURE

A hot-gas reciprocating machine having first and second compression and expansion spaces and pistons therein, a third piston within a third space which communicates with one of the first and second spaces, the two spaces in communication having pressure variations during operation, 90° out of phase with the pressure variations in the remaining space, and the stroke-volume of the first and second pistons being related by τ (τ being the quotient of the absolute temperatures prevailing in the second and first spaces respectively), for balancing the dynamic forces in operation of the apparatus and reducing the mechanical losses therein.

The invention relates to a hot-gas reciprocating machine comprising a first space the volume of which can be varied by a first piston-like body and to which heat can be supplied during operation, which space is connected to a second space the volume of which can also be varied by a piston-like body and from which heat can be derived during operation, which spaces in operation have relatively different mean temperatures, the link between these spaces accommodating a recuperator through which a working medium can flow to and fro.

In the present application, a hot gas reciprocating engine is to be understood to mean a cold-gas refrigerator, a hot-gas engine, a heat pump and a cold-gas engine. In these engines, a working medium is compressed when it is contained primarily in a space (compression space) from which heat can be derived, and this medium is expanded when it is contained primarily in a space (expansion space) to which heat can be supplied. The compression-and expansion spaces are separated by a regenerator. In known engines of the kind set forth, the volumes of the compression-and expansion spaces are varied by pistons which are displaced by a driving gear with a relative phase difference. The total volume variation of the compression space, the expansion space and the interposed link will be equal to the sum of the volume variations produced by the compression piston and the expansion piston together. These volume variations involve pressure variations, the phase difference between the compression piston and the expansion piston being chosen so that the pressure variations lead in phase to the movements of the compression piston and lag behind the movements of the expansion piston. The compression energy supplied by a compression piston is determined solely by that part of the pressure variations which leads in phase by 90° to the movements of this piston, while the expansion energy absorbed by an expansion piston is determined solely by that part of the pressure variations which lags by 90° in phase behind the movements of this piston. The other part of the relevant pressure variations is in co-phase or 180° phase difference with the movement of the piston and does not participate in the supply and absorption, respectively, of energy. Consequently, these pressure variations do not exert a favorable influence on the cycle passed by the medium. However, these pressure variations have the disadvantage that they of course do exert forces, so-called

blind forces, on the pistons and on the bearings so that they involve considerable mechanical losses.

The invention has for an object to provide a hot-gas reciprocating engine of simple construction, in which the pressure variations in the spaces from which heat can be derived and to which heat can be supplied, respectively, lag and lead, respectively, by at least substantially 90° in phase with respect to the movements of the relevant piston-like bodies.

The hot-gas reciprocating engine in accordance with the invention is therefore characterized in that the said piston-like bodies are connected to a driving gear which moves these bodies so that the volume variations of the space to which heat can be supplied are in phase opposition to those of the space from which heat can be derived, the stroke volume of the piston-like body for varying the volume of the space from which heat can be derived being substantially equal to τ times the stroke volume of the piston-like body for varying the space to which heat can be supplied, where τ is equal to the quotient of the absolute temperature prevailing during operation in the space from which heat can be derived and the absolute temperature prevailing in the space to which heat can be supplied. The engine also includes one or more further piston-like bodies which each limit by one side a space forming an open communication with the space from which heat can be derived and/or with the space to which heat can be supplied and/or with the link between these spaces, each of these piston-like bodies co-operating with a stroke limiter and/or a further energy-dissipating device which may be adjustable.

In this hot-gas reciprocating engine, each of the further piston-like bodies co-operates with a spring constituted by the medium in the spaces from which heat can be derived and to which heat can be supplied, respectively, and with a stroke limiter or another energy-dissipating device. Due to the difference in stroke volume of the piston-like bodies limiting the spaces from which heat can be derived and to which heat can be supplied, respectively, no pressure variation will occur during operation of this engine when the medium is transported from one space to the other. When each of the further piston-like bodies performs a movement which lags by 90° in phase behind the movement of the piston-like body varying the space from which heat can be derived, and hence leads by 90° to the movement of the piston-like body varying the space to which heat can be supplied, this is achieved because the pressure variations are in co-phase with the movements of the further piston-like body, the pressure variations are also by 90° out of phase with respect to each of the two said piston-like bodies. This implies that these piston-like bodies are no longer subjected to blind forces so that the mechanical loss is considerably reduced and the overall efficiency of the hot-gas reciprocating engine is higher. A phase difference of substantially 90° between the movements of each of the further piston-like bodies and the piston-like bodies varying the volumes of the spaces from which heat can be derived and to which heat can be supplied, respectively, is obtained automatically if the latter piston-like bodies move at least substantially at a frequency corresponding to the natural frequency of each of the further piston-like bodies and the co-operating spring and stroke limiter or other energy-dissipating devices. Since the stroke limiter or energy-dissipating device always requires some energy, if the further piston-like body does not co-operate with a driving member, the pressure variations cannot be fully in co-phase with the piston movements but will slightly lead in phase so that the further piston-like body receives some energy from the medium.

In the present application, a piston-like body is to include not only a piston or a plunger, but also a diaphragm. In a further advantageous embodiment of the hot-gas reciprocating engine according to the invention, the piston-like bodies for varying the volume of the spaces to which heat can be supplied and from which heat can be derived, respectively, are rigidly connected to each other, the centre lines of these piston-like bodies coincide and the space from which heat can be derived, the recuperator and the space to which heat can be supplied lie between the piston surfaces of the said piston-like bodies facing each other. Due to the rigid connection between the two piston-like bodies, the energy supplied to the expansion piston upon expansion is directly transmitted to the compression piston.

In another embodiment, the piston-like bodies for varying the volume of the spaces to which heat can be supplied and from which heat can be derived, respectively, are also rigidly connected to each other while the piston surfaces varying the volumes of said spaces are directed away from each other.

A further advantageous embodiment of the hot-gas reciprocating engine according to the invention is characterized in that each of the further piston-like bodies also co-operates with a further energy-accumulating device which may be adjustable. Thus, this engine includes besides the medium acting as energy accumulator an additional accumulator which also determines its speed. When this further accumulator device is made adjustable, the speed of the operating engine can be varied by varying the adjustment. According to the invention, the energy-accumulating device may comprise a spring or a flywheel which is connected, if desired, through a transmission, to the relevant piston-like body.

In a further embodiment, the energy-dissipating device comprises a double-acting piston which is connected to the further piston and is adapted to move in a closed cylinder containing a medium, the two spaces on either side of this piston communicating with each other through a narrow opening the passage of which may be adjustable. Also the energy-dissipating device may comprise a brake which may be adjustable, or the energy-dissipating device comprises a cooled tube which closed at one end and limited at its other end by a piston surface coupled with the piston-like body.

In a further favourable embodiment, in which the pressure variations are accurately in co-phase with the movements of each of the further piston-like bodies, these further piston-like bodies are connected, if desired through a transmission, to a driving member, the movements of each of the piston-like bodies lead at least substantially by 90° in phase to the movements of the piston-like body varying the volume of the space to which heat can be supplied. In this embodiment, each of the further piston-like bodies may be coupled with the crankshaft which also cooperates with the piston-like bodies varying the volumes of the spaces from which heat can be derived and to which heat can be suppled, respectively. Alternatively, the driving member may be constituted by a separate electric motor or another driving device rotating in the correct phase.

In order to compensate in this embodiment for the pressure forces acting upon each of the piston-like bodies, according to the invention, each further piston-like body has a stroke, a speed and a mass such that the inertia forces occurring in operation are at least substantially equal to the sum of the pressure variations and spring forces produced in co-phase with the piston movement.

The invention will be described more fully with reference to the drawings.

FIGURES 1 to 6 show diagrammatically and not to scale a number of embodiments of cold-gas refrigerators, in which the volumes of the compression- and expansion spaces vary in relative phase opposition and the ratio between the strokes of the piston-like bodies varying the volumes of these spaces is equal to that between the absolute temperatures prevailing during operation in these spaces. Provision is made of one or more further piston-like bodies which are each capable of varying the volume of a further space communicating with the compression- and/or expansion space, which these further piston-like bodies perform movements which are by 90° out of phase with respect to the piston-like bodies varying the volumes of the compression- or expansion space. The further piston-like bodies then co-operate with an energy-accumulating and an energy-dissipating device.

FIGURES 7 and 8 show two embodiments of cold-gas refrigerators which roughly correspond to the cold-gas refrigerators of FIGURES 1 to 6, but in which the further piston-like bodies are coupled with a driving member.

FIGURE 9 shows diagrammatically and not to scale an embodiment of a hot-gas engine in which the volumes of the compression- and expansion spaces again vary in relative phase opposition, while the ratio between the stroke volumes of the piston-like bodies varying the volumes of the compression- and expansion space is equal to the quotient of the absolute temperatures prevailing in these spaces during operation, provision being made of one or more further piston-like bodies which each vary the volume of a space communicating with the compression- or expansion space and which co-operate with an energy-dissipating and an energy-accumulating device.

Referring now to FIGURE 1, reference numeral **1** denotes a cylinder in which a compression piston **2** and an expansion piston **3** are adapted to move. The compression piston **2** and the expansion piston **3** are rigidly connected to each other by means of a link **4**. Between the piston surfaces facing each other of the pistons **2** and **3**, there are disposed a compression space **5**, a cooler **6**, a recuperator **7**, a freezer **8** and an expansion space **10**. The expansion piston **3** is connected through a driving rod **11** to a crankshaft **12** which is coupled with a driving member (not shown). The compression piston **2** has a larger diameter than the expansion piston **3** so that the stroke volume of the compression piston **2** is τ times that of the expansion piston **3**. τ represents the quotient of the absolute temperature prevailing in the compression space and that prevailing in the expansion space **10** during operation.

The cold-gas refrigerator further includes a cylinder **15** in which a further piston **16** is adapted to move. This piston **16** limits by one side a space **17** communicating with the compression space **5** and at by other side a space **18** in which prevails the same mean pressure as in the compression space **5**. The piston **16** is connected through a piston rod **19** to a piston **20** which is adapted to move in a closed cylinder **21** containing a liquid. The two spaces on either side of the piston **20** communicate with each other through a duct **22** including an adjustable shutter **23**. The piston **16** further co-operates with a spring **25**. The piston **16** and the co-operating spring system constituted by the medium in the spaces **17, 5, 6, 7, 8, 10** and the medium in the space **8** and the spring **25** has a given natural frequency depending upon the spring constant of the said spring system and upon the mass of the moving parts

When, after putting the cold-gas refrigerator in operation, the crankshaft is driven at the said natural frequency due to the fact that the same temperature prevails in the spaces **5** and **10**, pressure fluctuations resulting from the difference in diameter of the pistons **2** and **3** will be produced at a frequency equal to the natural frequency of the piston **16**. As a result, the piston **16** starts moving at its natural frequency, which movements lag, however, by 90° in phase behind these pressure fluctuations. This implies that the movements of the piston **16** will also lag by 90° in phase behind the movements of the compression piston **2**, but will lead by 90° in phase to the movements of the expansion piston **3**. The pressure fluctuations produced by the movements of the piston **16** will then lead by 90° in phase to the movements of the piston **3**. This implies that the piston **2** is a compression piston and piston **3** is an expansion piston.

The medium will be compressed when it is mainly contained in the space **5**, the compression heat being derived from the medium in the cooler **6**. The medium is expanded when it is mainly contained in space **10**, heat, for example, of an article or a medium to be cooled, being supplied to the medium in the freezer **8**. The temperature in the space **10** will be low, while the space **5** will be approximately at the cooling-water temperature. The stroke volumes of pistons **2** and **3** are chosen so that they are in the same ratio as the absolute temperatures prevailing in operation in the compression space **5** and in the expansion space **10**. This means that during operation, i.e. when the expansion space **5** is at the cooling-water temperature and the expansion space **10** is at a low operating temperature, movements of the pistons **2** and **3** no longer produce pressure fluctuations. Pressure fluctuations are then produced only by the vibrating piston **16** which are in co-phase with the movements of this piston. This means that the pressure fluctuations then produced are at right angles to the movements of the compression piston **2** and the expansion piston **3** so that blind forces resulting from pressure fluctuations which are in co-phase with these pistons are avoided in this refrigerator, which will therefore operate with low mechanical losses. In order to limit its stroke, the piston **16** co-operates with a damping device **20, 21, 22, 23** in which an amount of energy is dissipated. In order to maintain the vibration of the piston **16**, a quantity of energy will have to be supplied to said piston. Consequently, the pressure fluctuations in the spaces **17, 5, 6, 7, 8** and **10** will slightly lead with respect to the movements of this piston.

FIGURE 1 shows in dotted lines that an alternate cylinder **15'** and a piston **16'** adapted to move therein, may be connected to the space **10**. This piston **16'** shown in dotted lines will move in co-phase with the piston **16** described above.

FIGURE 2 shows diagrammatically the same cold-gas refrigerator as FIGURE 1, but in this case, the compression piston **2** and the expansion piston **3** are interconnected inside by means of a rod **25**. This provides a slightly more aesthetic construction. In this embodiment, the piston **16** co-operates with a slightly modified spring- and damping system. The side of the piston **16** remote from the space **17** limits a space **30** which communicates with a space **33** through a duct **31** including a shutter **32**. The spaces **30** and **33** contain a gas at the mean pressure prevailing in the space **17**. The operation of this cold-gas refrigerator is quite analogous to that of the cold-gas refrigerator of FIGURE 1.

FIGURE 3 shows a cold-gas refrigerator having a slightly modified construction. This cold-gas refrigerator has two interconnected pistons **32** and **33** which vary the volumes of a compression space **35** and of an expansion space **40** by their piston surfaces remote from each other. The compression space **35** communicates through a cooler **36**, a recuperator **37** and a freezer **38** with the expansion space **40**. The compression space **35** again communicates with a space **17** which is limited by a piston **16** which is adapted to move in a cylinder **15**; the arrangement is quite analogous to that of FIGURE 1. This refrigerator also operates in quite the same manner as the refrigerators of the preceding figures.

FIGURE 4 shows a cold-gas refrigerator which corresponds to that of FIGURE 3, but in which the piston **16** also limits the expansion space **40**. When the crankshaft **12** is moved again at the natural frequency of the piston **16**, the piston **16** will again start vibrating and its movements will lead by 90° in phase to the piston surface of the piston **32** varying the volume of the compression space **35** and will lag by 90° in phase behind the piston surface of the piston **33** which also varies the volume of the space **40**, so that this cold-gas refrigerator again operates in the same manner as that of FIGURE 1.

FIGURE 5 shows the same cold-gas refrigerator as FIGURE 4, but in this case, the energy-dissipating device is constituted by a tube **50** which is closed at one end and is limited at its other end by a piston **51** which is connected by means of a rod **52** to the piston **16**. When the tube **50** is cooled externally, for example, by means of a cooling helix **53**, a reciprocating movement of the piston **16** and the piston **51** coupled therewith will result in a phase shift of the pressure variations in the tube **50** with respect to the movements of the piston **51** so that energy is absorbed. By varying the extent of cooling, the dissipated power can be adjusted.

FIGURE 6 shows a cold-gas refrigerator of the same construction as that shown in FIGURE 1, but in this case, the piston **16** does not co-operate with a liquid damper but with a flywheel **60** which is connected by means of a long driving rod **61** to the piston **16**. This flywheel thus acts as a stroke limiter and as an energy-accumulating device.

FIGURE 7 shows a cold-gas refrigerator having a compression piston **72** and an expansion piston **73** which are rigidly interconnected by means of a rod **74**, while a compression space **75**, a cooler **76**, a recuperator **77**, a freezer **78** and the expansion space **79** are disposed between the piston surfaces of the pistons **72** and **73** facing each other. The compression piston **72** is connected by means of a driving rod **81** to a crank **82** of a crankshift **83**. The crankshaft **83** is connected to a driving member (not shown). The crank **82** is further connected by means of a driving rod **84** to a further piston **85**, the centre lines of the piston **85** and of the pistons **73** and **72** being at an angle to each other of 90°. A space **86** communicating through a duct **87** with the compression space **75** is located above the piston **85**. When the crankshaft **83** is driven in the direction of the arrow, the movements of the surface of the piston **85** facing the space **86** will lag by 90° in phase behind the surface of the compression piston **72** facing the space **75** and will lead by 90° in phase to the surface of the expansion piston **73** facing the expansion space **79**. The mass of piston **85**, the spring constant of the spring system co-operating with these pistons and the speed are adjusted so that the inertia forces produced just cancel the pressure variations.

Thus, a cold-gas refrigerator is obtained in which the pressure variations in the medium lag by accurately 90° in phase behind the movements of the compression piston **72** and lead by accurately 90° in phase to the movements of the expansion piston **73**. Thus, no blind forces will be exerted on these pistons.

FIGURE 8 shows diagrammatically a slightly modified embodiment of the cold-gas refrigerator shown in FIGURE 7, in which piston **85** cooperates through a liquid column **88** with a piston **89** for varying the volume of a space **90** which is in open communication with the compression space **75**. This refrigerator operates in quite the same manner as that of FIGURE 7. The masses of the pistons **85** and **89** and the liquid column **88**, the spring constant of the spring system and the speed are relatively tuned.

The statements made with respect to the gold-gas refrigerators shown in the preceding figures roughly also apply to a hot-gas engine, however, the difference in temperature between the compression space and the expansion space in the hot-gas engine deviates from that in the cold-gas refrigerator. In the hot-gas engine, the expansion takes place at higher temperature and the compression space is again at the cooling-water temperature. This means that τ has a value which is smaller than 1. Thus, in a hot-gas engine, the expansion piston will have a larger stroke volume than the compression piston. This can be seen in the hot-gas engine shown diagrammatically in FIGURE 9. The hot-gas engine of FIGURE 9 has a compression piston **92** and an expansion piston **93** which are rigidly interconnected by means of a connecting rod **94**. A compression space **95**, a cooler **96**, a recuperator **97**, a heater **98** and the expansion space **100** are located between the surfaces of the said pistons facing each other. The expansion piston **93** is connected by means of a piston rod **101** to a crankshaft **102** which is coupled with a device to be driven (not shown in the drawing). The hot-gas engine further includes a cylinder **105** in which a piston **106** is adapted to move which limits by one side a space **107** which is in open communication with the compression space **95** and by the other side a space **108** in which the mean pressure prevails. The piston **106** is connected through the rod **109** to a piston **110** which is adapted to move in a close cylinder **111** completely filled with a liquid, the two spaces on either side of the piston **110** communicating with each other through a duct **112** including an adjustable shutter **113**. Like in the cold-gas refrigerator of FIGURE 1, the piston **106** will start vibrating and the pressure variations produced by the movements of the piston **106** lead by 90° to the movements of the piston **92** and lag by 90° behind the movements of the piston **93**. The speed of this hot-gas engine is adjustable by varying the spring constant of a spring system with which the piston **106** co-operates. The power supplied by this hot-gas engine may also be adjusted by a variation of the stroke of the piston **106**, resulting from a variation of the adjustment of the shutter **113**.

What is claimed is:

1. An apparatus such as a hot and cold gas machine comprising a first space the volume of which can be varied by a piston and to which heat can be supplied during operation, which space is connected to a second space the volume of which can also be varied by a piston and from which heat can be derived during operation, these spaces having in operation relatively different mean temperatures, while the link between these spaces includes a recuperator through which a working medium can flow to and fro, characterized in that the said piston *s* are connected to a driving gear which moves these pistons so that the volume variations of the first space are in co-phase with the volume variations of the second space, while the stroke volume of the second piston for varying the volume of the second space is substantially equal to τ times the stroke volume of the piston for varying the volume of the first space, τ being equal to the quotient of the absolute temperatures prevailing during operation in the second and first spaces, while the apparatus further includes (i) a cylinder and a third piston therein defining a third space on one side of the third piston, the third space being in open communication with one of the first and second spaces or with the link between these spaces, and ((i) an adjustable means for limiting the stroke of the third piston.

2. In apparatus such as hot gas and cold gas reciprocating machines, each having at least first and second separate spaces for compression and expansion and corresponding first and second pistons therein for varying the volumes of said spaces which are interconnected by a regenerator link through which medium flows alternately in both directions during operation, the spaces having relatively different mean temperatures with heat

being supplyable to one space and removable from the other, the improvement in combination therewith comprising:

- means fixedly joining the two pistons which are movable to vary the volumes of the first and second spaces in co-phase relationship, and
- means including (i) an enclosure with a third space therein in communication with one of the first and second spaces or their interconnecting link, and (ii) a third piston operable in the third space, whereby the pressure variations of the third space and the space with which it communicates are out of phase with the pressure variations of the remaining space.

3. Apparatus as defined in claim **2**, wherein the stroke volumes of the first and second pistons respectively are substantially related by τ (τ being equal to the quotient of the absolute temperatures prevailing during operation in the second and first spaces respectively).

4. Apparatus as defined in claim **3** wherein said pressure variations are out of phase by approximately 90°.

5. Apparatus as defined in claim **4**, further comprising means for limiting the stroke of the third piston to provide said pressure variations.

6. Apparatus as defined in claim **5**, further comprising energy-dissipating means operable with the third piston for urging said third piston to oscillate at its natural frequency.

7. Apparatus as defined in claim **6** wherein said stroke-limiting means and said energy storage means are formed by a flywheel connected to said third piston.

8. Apparatus as defined in claim **6** wherein said energy-dissipating means is a spring.

9. Apparatus as defined in claim **5** wherein said stroke-limiting means is a dash-pot.

10. Apparatus as defined in claim **4** wherein said first and second pistons are coaxial.

11. Apparatus as defined in claim **2** wherein said third piston and enclosure defines said third space on one side of the piston and a fourth space on the opposite side of the piston, the fourth space having substantially the same mean pressure prevailing therein as in the first and second spaces.

12. Apparatus as defined in claim **6** wherein said energy-dissipating means is a coolable tube closed at one end and limited at the other end by a piston surface coupled to said third piston, and means for cooling said tube.

13. Apparatus as defined in claim **6** wherein the third piston has stroke, velocity, and mass selected such that the inertia forces produced during operation of the apparatus are substantially equal to pressure variations produced by the first and second pistons.

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WILLIAM J. WYE, Primary Examiner

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60—24