July 6, 1937. H. JUNKERS 2,086,163

FREE PISTON ENGINE

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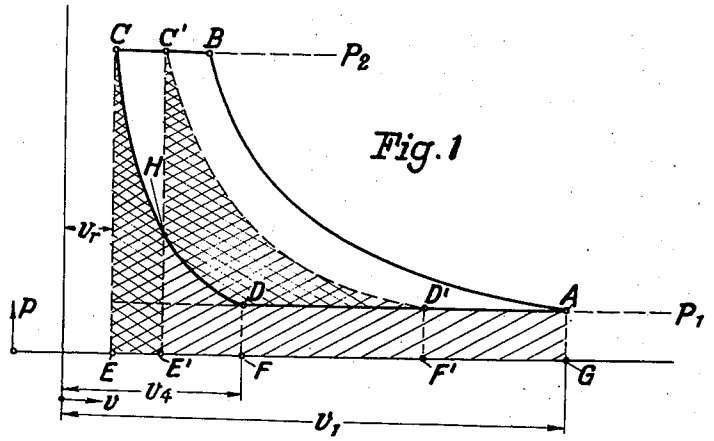


Fig. 1

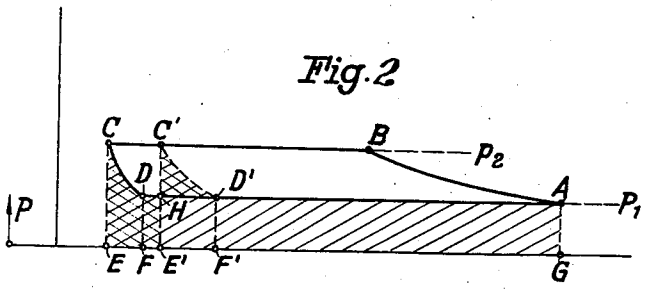


Fig. 2

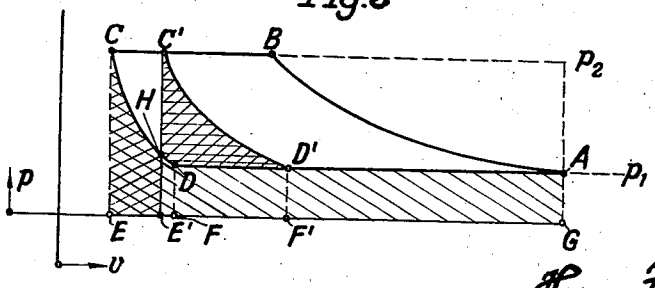


Fig. 3

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FREE PISTON ENGINE

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Fig. 4

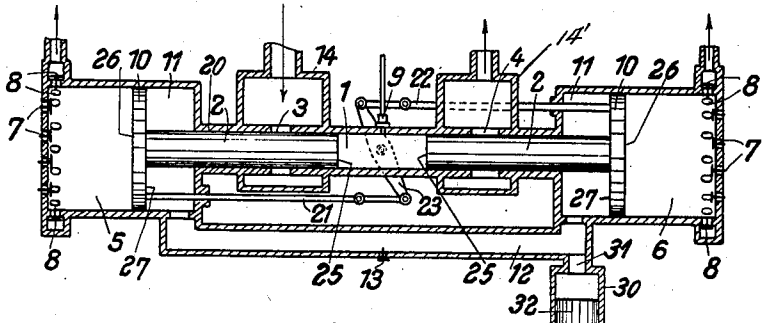
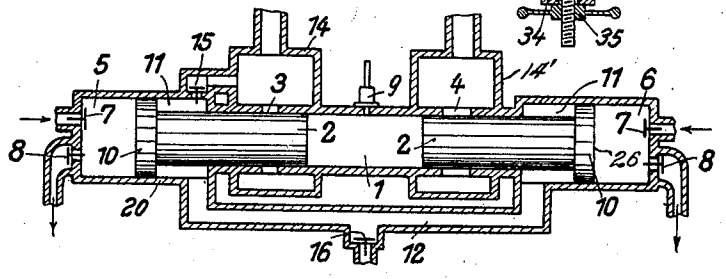


Fig. 5



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Patented July 6, 1937 2,086,163

UNITED STATES PATENT OFFICE

2,086,163

FREE PISTON ENGINE

Hugo Junkers, Dessau, Germany; Therese Junkers, née Bennhold, Gauting, Germany, administratrix of said Hugo Junkers, deceased

Application January 9, 1934, Serial No. 705,906
In Germany January 18, 1933

7 Claims. (Cl. 230—56)

My invention relates to free piston engines in which a free piston or a pair of such pistons is or are arranged in a cylinder for reciprocation. It is an object of my invention to improve the efficiency of this type of engines.

In free piston engines a mixture of fuel and air introduced into the space on one side of the piston, if only a single piston is provided, or into the space between the pistons if two pistons are provided (these spaces being referred to hereinafter as combustion chambers) and ignited causes the piston or pistons to move outwardly and to compress bodies of gas provided in the end portion or portions of the cylinder (referred to hereinafter as compression chambers) thereby transmitting to the gas energy which can be utilized in any suitable manner. In order to return each piston to its inner dead centre positions, it is necessary to feed part of this energy back to the piston. The stroke of the piston is not constant, but is varied either unintentionally, for instance when the friction between the piston and the wall of the cylinder is altered, or intentionally in order to control the delivery of the engine.

It is an object of my invention to operate a free piston engine in such manner that the inner dead centre positions of the pistons are not altered by variations of the stroke of the pistons, so that the compression of the charge in the combustion chamber is independent of the stroke of the piston or pistons and the driving part of the engine operates in the most efficient manner. Under these conditions a variation of the stroke of the piston merely affects the outer dead centre position of each piston, the inner dead centre position remaining unaltered. In order to accomplish this, it is necessary that the total amount of energy fed back by the gas to the pistons during their return stroke hereinafter called feed-back energy be substantially constant and independent of the stroke.

If this amount of feed back energy were to drop considerably, the charge in the motor cylinder would also be less compressed, so that a motor with ignition by compression (Diesel motor) might be put out of operation. On the other hand, if the feed back energy were to rise considerably in consequence of a change of stroke, the charge of the motor cylinder would also be compressed far more and during the combustion to follow the pressure and temperature would rise correspondingly, far beyond the normal, so that the motor would be endangered.

In order to maintain the feed-back energy constant and independent of the stroke, it has been proposed to provide separate gas-filled buffer cylinders which do not transmit energy from the engine to a consumer, but merely store energy during the working stroke and feed it back to the piston during its return stroke. When using such buffer cylinders, a resultant feed back energy, which remains substantially constant in spite of variations of stroke, would be obtained only in the case where that part of the feed back energy, which is generated in the compressor cylinders, increases, while the stroke decreases. However, as shown farther below, this will be the case only if the compressor operates with a high ratio of compression (feed pressure : suction pressure). The addition of such separate buffer cylinders increases the number of parts in the engine and the space required for it. For this latter reason, one always tries to keep these buffers as small as possible and on the other hand to operate them with high pressures. However operation under high pressures impairs the safety of operation of the machine, since in consequence of the high compression the gas in the buffers is highly heated, so that the parts are subjected to high heat stresses.

It is an object of my invention to provide an improved free piston engine in which the feed-back energy is substantially constant and independent of the stroke of the piston or pistons, whereby buffers to be separately added or which must be operated under high pressure can be dispensed with.

In order that my invention may be fully understood, reference is had to the accompanying drawings forming part of this specification and showing by way of example some embodiments of free piston engines according to my invention and some diagrams explaining the operation of the engines.

In the drawings:

Figs. 1–3 are diagrams serving for the explanation of the operation of this engine,

Figs. 4 and 5 are axial sections of two embodiments of an engine according to my invention.

Referring first to Fig. 1, in which the abscissae designate the volume v, the ordinates the pressure p of the gas in the compression chamber, be it assumed that p_1 and v_1 are the pressure and the volume respectively of the gas in the compression chamber at the inner dead centre position of the piston, while p_2 is the pressure in the compression chamber at the outer dead centre position of the piston. Fig. 1 illustrates the volume-pressure diagrams for two strokes having different lengths and equal inner dead centre positions. At the beginning of the outward stroke of the piston the pressure and the volume are equal to p_1 and v_1, respectively, this condition being indicated by the point A. During the first portion of the outward stroke the compression of the gas in the compression chamber is effected along the curve A, B, the pressure rising to the value p_2. Now compressed gas is expelled from the compression chamber till the piston reaches its outer dead centre position, the corresponding curve being a horizontal straight line B, C. C corresponds to the outer dead centre position of the piston and the first portion of the return stroke is effected along the curve C, D, the pressure dropping to p_1 when the point D is reached. During the last portion of the return stroke corresponding to the horizontal straight line D, A fresh gas or air is sucked into the compression chamber. v_r and v_4 are the volumes corresponding to the points C and D, respectively. The feed-back energy can be calculated from this diagram and is equal to the area of the surface G, A, D, C, E, G.

For a shorter stroke of the piston the diagram consists of the curve A, B, C', D' and the feed-back energy corresponding to this stroke is given by the area of the surface G, A, D', C', E', G. In order to compare the feed-back energies in both cases with each other, merely the cross-hatched areas in Fig. 1 are to be compared since the area G, A, D, H, E', G is a portion of both areas. A comparison of the cross-hatched areas D', C', H, D, D' and E', H, C, E, E' shows that the feed-back energy increases with decreasing length of stroke.

In Fig. 1 the ratio $p_2:p_1$ is relatively high. Fig. 2 shows the diagram for the same stroke, the ratio $p_2:p_1$ however being relatively low. In order to compare the feed-back energies in this case, the areas of the surfaces D', C', H, D' and E', H, D, C, E, E' are to be compared with each other and the figure shows that the feed-back energy increases with increasing length of stroke.

Thus Figs. 1 and 2 show that for high ratios $p_2:p_1$ the feed-back energy decreases with increasing stroke, while for lower ratios $p_2:p_1$ the feed-back energy increases with increasing stroke. The same result can be arithmetically calculated from the formula given below for the feed-back energy.

From the foregoing it can be concluded that there exists a value of the ratio $p_2:p_1$ for which the feed-back energy is constant and independent of the length of the stroke without any special measures, such as the use of buffers, need be resorted to.

Fig. 3 shows the diagram of a compressor, in which the ratio

$$\frac{p_2}{p_1}$$

is so chosen, that the feed back energy remains constant also on the length of stroke being changed. In the diagram this can be guessed from the fact that the surface C, H, E', E, C for the longer stroke up to C and the surface C', D', D, H, C' for the shorter stroke up to C' are equal. This ratio of pressures can be arithmetically calculated as follows: The area L_1 of the surface F, D, C, E, F is given by the following formula (see Schüle, Technische Thermodynamik, 4th edition, page 114)

$$L_1=\frac{p_1 \cdot v_1}{m-1}\left(\left(\frac{p_2}{p_1}\right)^{\frac{m-1}{m}}-1\right)$$

m being the coefficient of expansion of the gas in the compression chamber. p_1 and p_2 have been defined above, v_4 is the volume of the gas in the compression chamber corresponding to point D. The area of the surface G, A, D, F, G, is equal to

$$L_2=(v_1-v_4)\cdot p_1$$

In consequence thereof the feed-back energy, being the sum of L_1 and L_2, is equal to

$$L=L_1+L_2=p_1 \cdot v_4 \frac{\left(\frac{p_2}{p_1}\right)^{\frac{m-1}{m}}-1}{m-1}+(v_1-v_4)p_1$$

The feed-back energy L depends on the volume v_4 so that generally it is not constant and depends on the length of the stroke. If however $p_2:p_1$ is equal to

$$m^{\frac{m}{m-1}}$$

it will be seen that the feed-back energy L has the value $v_1 \cdot p_1$ and is independent of the length of the stroke. If it is assumed that the curves A, B and C, D are adiabatics, m is equal to 1.4 and the ratio $p_2:p_1$ is equal to 3.25. In the diagram shown in Fig. 3 $p_2:p_1$ has this value and the cross-hatched surfaces have equal areas.

This invention relates to free piston motor compressors in which the compressor piston is larger than the motor piston, so that on the side of the compressor piston facing the motor piston an annular surface remains over of a size equal to the difference in size of the two piston surfaces. It is known to keep this annular surface permanently in contact with the free atmosphere and it is further known to utilize the space of the compressor cylinder, which adjoins this annular surface, for the compression and conveying of gas. The energy required therefor must be furnished by the amount of energy which is available in the compressor space adjoining the outer surface of the compressor piston, when the freely moving mass passes through its return stroke. The same amount of energy must however also be resorted to for the compression of the charge of the motor cylinder. However the remainder of energy still available will in general be very small so that a high compression of the charge of the motor cylinders such as is required for the operation of free piston engines according to the Diesel process cannot be carried through any more.

According to the present invention I succeed in operating the motor part according to the Diesel process and in obtaining a magnitude of the energy serving for compressing the motor charge, which remains substantially constant regardless of variations in the stroke of the freely movable masses by choosing the ratio of pres-

sures in the compressor space adjoining the outer surface of the compressor piston smaller than

$$\frac{m}{m^{m-1}}$$

(wherein m is the coefficient of expansion) and by further closing up the space adjoining the annular rear surface of the compressor piston, at the same time filling this space with a predetermined quantity of gas, which during the reciprocation of the freely moving mass is alternately compressed and expanded. When the stroke of the freely moving masses rises, the amount of energy taken up by this quantity of gas during its compression will rise also and reversely it will diminish as the stroke of the freely moving masses drops. For the compression of the motor charge there is available the difference between the energy liberated in the compressor space and the energy taken up in this annular space. Now, since for instance when the stroke of the freely moving masses drops, the energy liberated in the compressor space and similarly the energy taken up by the annular space become smaller, the difference between these two amounts of energy will remain approximately constant, provided that the magnitudes of the spaces and pressures in the compressor space and in the annular space are so chosen, that the amounts of energy liberated in the compressor space and taken up in the annular space vary to the same extent during a variation of stroke.

In actual practice one finds that in most cases which occur practically, in order that the desired effect be obtained, the gas enclosed in the annular space need possess only a comparatively low medium pressure and only small variations of this pressure. This offers great advantages for the operation of the machine since consequently also stresses arising from pressure and heat in the parts of the machine surrounding the annular space are only insignificant and since apart therefrom there is always available a resultant back-feed energy sufficing for a high compression of the charge of the motor cylinder, i. e. for the Diesel operation of the motor part. Besides this, the magnitude of the feed-back energy, which becomes available in the compressor chamber, can be varied within certain limits without influencing the compressor output by choosing the dimensions of the dead space of the compressor in proportion. For instance, while the output of the compressor remains unchanged, there corresponds to a larger dead space also a larger surface of the compressor piston than with a small dead space and consequently also an increase of the energy which becomes available in the compressor chamber during the return stroke. The magnitude required in each individual case of the medium pressure and the required magnitude of the variations of pressure of the quantity of gas enclosed in the annular space, can easily be obtained by suitably choosing the dimensions of this space and the volume of gas enclosed therein. It is therefore easily possible to tune the magnitudes of the energies, the difference between which represents the resultant energy available for the compression of the charge of the motor cylinder in such manner that on one hand one obtains the desired high compression of the motor charge and that on the other hand this resultant quantity of energy remains approximately constant also during variations of the stroke of the freely moving masses.

Figs. 4 and 5 illustrate in a diagrammatical manner two embodiments of a machine according to the present invention. Similar parts are marked with similar numerals. Each of the two free piston motor compressors comprises in a well known manner a stationary cylinder **20** with enlarged ends **5**, **6**, in which reciprocate counter to each other two freely moving masses **2**, **10**, each formed by a smaller motor piston **2** and the larger compressor rigidly connected with it. The end faces **25** of the motor pistons **2**, which face each other, enclose between them the working chamber **1** of the motor. The outer end faces **26** form the end walls of the compressor spaces formed by the enlargements **5** and **6** of the casing. The annular rear surfaces **27** of the pistons **10** delimit spaces **11**, which communicate permanently with each other through a conduit **12**. The spaces **11** and conduit **12** are filled with a predetermined quantity of gas which permanently remains therein. **7** are the suction valves, **8** the pressure valves of the compressors, **9** is a device for feeding fuel to the motor cylinder, **3** are the inlet ports and **4** the outlet ports of the motor cylinder. These ports are uncovered and covered by a motor piston **2** of their own during its reciprocation. The exhaust gases pass from the cylinder through the ports **4** into the exhaust chamber **14'**. In a machine of this kind the feed-back energy will be constant and independent of the length of the stroke by choosing a pressure ration $p_2:p_1$ equal to

$$\frac{m}{m^{m-1}}$$

only if the intermediate chambers **11** are evacuated and no gas pressure exists therein. In practice, however, it is very difficult to accomplish this and in consequence thereof I provide means for maintaining the feed-back energy constant even if a gas pressure is exerted on the rear faces **27** of the end portions **10** of the pistons. These means are based on the following reasoning:

Assuming that an invariable amount of gas is included in an intermediate chamber **11**, this amount of gas will be compressed during the return stroke of the piston. In consequence thereof energy is fed to this gas and this energy increases with the length of the stroke. It can only be supplied from the energy fed back by the gas in the compression chamber during the return stroke of the piston. In consequence thereof the ratio $p_2:p_1$ should be chosen in such manner that the difference between the feed-back energy and the energy stored during the return stroke in the intermediate chamber **11** is constant and independent of the length of the stroke in order to obtain a constant energy for compressing the charge in the combustion chamber **1**. In order to accomplish this the ratio $p_2:p_1$ in the compression chamber must not be made exactly equal to

$$\frac{m}{m^{m-1}}$$

but should be somewhat smaller so that the feed-back energy increases with an increase of the stroke to an amount corresponding to the simultaneous increase of the energy stored in the intermediate chamber.

The amount of the feed-back energy depends upon the ratio between the areas of the surfaces **25** and **26**. This ratio can be varied within certain limits without changing the power of the

compressor, provided that at the same time the dead space of the compressor is dimensioned accordingly. The dead space should be the larger, the larger the area of the piston surface 26.

The amount of energy to be stored in the intermediate chamber 11 during the return stroke of the piston substantially depends on the average pressure existing in the intermediate chamber. The necessary value of this pressure and the desired variation thereof in dependency from the length of the stroke can easily be obtained by suitably dimensioning the volume of the chamber and the amount of gas enclosed therein.

In Fig. 4 the intermediate chambers 11 are connected with each other by a pipe 12, and by suitably dimensioning the volume of this pipe with respect to that of the chambers 11 the average pressure existing in the intermediate chambers 11 can be adjusted. If for instance the pressure in the intermediate chambers 11 and the pipe 12 is equal to the atmospheric pressure at the inner dead centre position of the pistons, this pressure will decrease during the outward stroke, but will rise to its former value during the return stroke of the freely moving masses. This change of pressure becomes the greater, the smaller the part of the spaces 11, 12, which is not passed by the piston 10, more especially therefore the smaller the volume of the conduit 12. The higher the change of pressure, the greater is also (at a predetermined starting pressure) the amount of energy taken up by the gas contained in the spaces 11, 12 during the return stroke. Therefore if the space 11, 12 is made variable as to its volume, without changing the quantity of gas enclosed therein, the pressure ratio in the compressor cylinders can also be varied within certain limits without renouncing to the advantage offered by the approximate constancy of the resulting feed back work. In order to change this volume at will the pipe 12 may be provided with a clearance chamber 30, the upper portion of which communicates with the interior of pipe 12 by means of a port 31. A piston 32 is provided with a threaded piston rod 33 extending through the end wall 34 of the cylinder 30. 35 is a nut engaging the threaded piston rod 33 and rotatably supported by the end wall 34. By rotating the nut 35 the position of the piston 32 and thus the volume of the space connecting the intermediate chambers 11 can be varied.

The maximum pressure existing in the chambers 11 and in the connection 12 may differ from atmospheric pressure. It may for instance be equal to the pressure in the scavenging air chamber 14. Preferably the intermediate chambers 11 and the connection 12 communicate with a space in which the maximum pressure exists, for instance with the atmosphere, or with the chamber 14 by means of a check valve opening into said space. A valve of this kind is indicated at 13 in Fig. 4. This valve prevents the pressure within the intermediate chambers 11 from exceeding atmospheric pressure even if the enlarged portions 10 of the pistons are not perfectly packed in the enlarged portions of the cylinder.

In Fig. 4 the pistons 2 are mechanically coupled with each other by means of rods 21 and 22 linked to a double armed lever 23 pivoted about its middle point. In consequence thereof the pistons reciprocate in opposite directions.

Fig. 5 shows an embodiment similar to that shown in Fig. 4. Here the intermediate chambers 11 are connected to the chamber 14 to which the scavenging air is fed by a separate pump (not shown) in the direction of the arrow in Fig. 4 by a check valve 15 opening into the chamber 14. In consequence thereof the pressure in the intermediate chambers cannot exceed the pressure in the chamber 14. On the other hand the pipe 12 communicates with a space, for instance the atmosphere, in which exists the minimal pressure to be maintained in the intermediate chambers 11, by means of a valve 16 opening into the pipe 12. As soon as the lower limit of the pressure prevailing in the spaces 11, 12 starts dropping below the atmospheric pressure, this valve 16 will open and admit air into the spaces 11, 12, until the lower limit of pressure in these spaces again corresponds to atmospheric pressure. In consequence thereof the pressure in the intermediate chambers 11 is always maintained between atmospheric pressure and the pressure in the scavenging air chamber 14, even if the pistons 2 and their enlarged end portions 10 are not perfectly packed in their cylinders. If desired the pipe 12 may be provided with an extension and an adjustable piston therein similar to that shown in Fig. 4.

I wish it to be understood that I do not desire to be limited to the exact details of construction shown and described, for obvious modifications will occur to a person skilled in the art.

I claim:—

1. A free piston engine comprising a cylinder having enlarged end portions, a pair of free pistons arranged in said cylinder, enlarged end portions of said piston being fitted into the end portions of said cylinder, a compression chamber and an intermediate chamber in each end portion of said cylinder, said chambers being separated from each other by an end portion of said piston, a conduit connecting said intermediate chambers with each other and a body of gas in each compression chamber and in the intermediate chambers and in said conduit, the ratio of the pressures of each body of gas in a compression chamber at the outer and inner dead centre positions of said pistons being less than

$$\frac{m}{m^{m-1}}$$

m being the coefficient of expansion of the gas, the average gas pressure in said intermediate chambers being so chosen that the difference of the total amounts of the energy fed by the gas to said pistons during their return stroke and of the energy stored in said intermediate chambers during the return stroke is substantially constant.

2. A free piston engine comprising a cylinder having an enlarged end portion, a free piston arranged in said cylinder, an enlarged end portion of said piston fitting into the enlarged end portion of said cylinder, a compression chamber and an intermediate chamber in said enlarged end portion of said cylinder, said chambers being separated from each other by said enlarged end portion of said piston, and a body of gas in said compression chamber and in said intermediate chamber, respectively, the ratio of pressures of the body of gas in said compression chamber at the outer and inner dead centre positions of said piston being less than

$$\frac{m}{m^{m-1}}$$

m being the coefficient of expansion of the gas, while the body of gas in said intermediate cham-

ber has an average pressure such that the difference between the energy fed by the gas to said pistons during their return stroke and the energy stored in said intermediate chamber during the return stroke is substantially constant.

3. A free piston engine comprising a cylinder having an enlarged end portion, a free piston arranged in said cylinder, an enlarged end portion of said piston fitting into the enlarged end portion of said cylinder, a compression chamber and an intermediate chamber in said enlarged end portion of said cylinder, said chambers being separated from each other by said enlarged end portion of said piston, and a body of gas in said compression chamber and in said intermediate chamber, respectively, the ratio of pressures of the body of gas in said compression chamber at the outer and inner dead centre positions of said piston being less than

$$m^{\frac{m}{m-1}}$$

m being the coefficient of expansion of the gas, while the body of gas in said intermediate chamber has an average pressure such that the difference between the energy fed by the gas to said pistons during their return stroke and the energy stored in said intermediate chamber during the return stroke is substantially constant, and means for varying the gas pressure in said intermediate chamber.

4. A free piston engine comprising a cylinder having an enlarged end portion, a free piston arranged in said cylinder, an enlarged end portion of said piston fitting into the enlarged end portion of said cylinder, a compression chamber and an intermediate chamber in said enlarged end portion of said cylinder, said chambers being separated from each other by said enlarged end portion of said piston, and a body of gas in said compression chamber and in said intermediate chamber, respectively, the ratio of pressures of the body of gas in said compression chamber at the outer and inner dead centre positions of said piston being less than

$$m^{\frac{m}{m-1}}$$

m being the coefficient of expansion of the gas, while the body of gas in said intermediate chamber has an average pressure such that the difference between the energy fed by the gas to said pistons during their return stroke and the energy stored in said intermediate chamber during the return stroke is substantially constant, and means for varying the volume of said intermediate chamber.

5. A free piston engine comprising a cylinder having an enlarged end portion, a free piston arranged in said cylinder, an enlarged end portion of said piston fitting into the enlarged end portion of said cylinder, a compression chamber and an intermediate chamber in said enlarged end portion of said cylinder, said chambers being separated from each other by said enlarged end portion of said piston, and a body of gas in said compression chamber and in said intermediate chamber, respectively, the ratio of pressures of the body of gas in said compression chamber at the outer and inner dead centre positions of said piston being less than

$$m^{\frac{m}{m-1}}$$

m being the coefficient of expansion of the gas, while the body of gas in said intermediate chamber has an average pressure such that the difference between the energy fed by the gas to said pistons during their return stroke and the energy stored in said intermediate chamber during the return stroke is substantially constant, and means for maintaining the gas pressure in said intermediate chamber below a predetermined maximum.

6. A free piston engine comprising a cylinder having an enlarged end portion, a free piston arranged in said cylinder, an enlarged end portion of said piston fitting into the enlarged end portion of said cylinder, a compression chamber and an intermediate chamber in said enlarged end portion of said cylinder, said chambers being separated from each other by said enlarged end portion of said piston, and a body of gas in said compression chamber and in said intermediate chamber, respectively, the ratio of pressures of the body of gas in said compression chamber at the outer and inner dead centre positions of said piston being less than

$$m^{\frac{m}{m-1}}$$

m being the coefficient of expansion of the gas, while the body of gas in said intermediate chamber has an average pressure such that the difference between the energy fed by the gas to said pistons during their return stroke and the energy stored in said intermediate chamber during the return stroke is substantially constant, and means for maintaining the gas pressure in said intermediate chamber above a predetermined minimum.

7. A free piston engine comprising a cylinder having an enlarged end portion, a free piston arranged in said cylinder, an enlarged end portion of said piston fitting into the enlarged end portion of said cylinder, a compression chamber and an intermediate chamber in said enlarged end portion of said cylinder, said chambers being separated from each other by said enlarged end portion of said piston, and a body of gas in said compression chamber and in said intermediate chamber, respectively, the ratio of pressures of the body of gas in said compression chamber at the outer and inner dead centre positions of said piston being less than

$$m^{\frac{m}{m-1}}$$

m being the coefficient of expansion of the gas, while the body of gas in said intermediate chamber has an average pressure such that the difference between the energy fed by the gas to said pistons during their return stroke and the energy stored in said intermediate chamber during the return stroke is substantially constant, and means for maintaining the gas pressure in said intermediate chamber between predetermined maximum and minimum limits.

HUGO JUNKERS.