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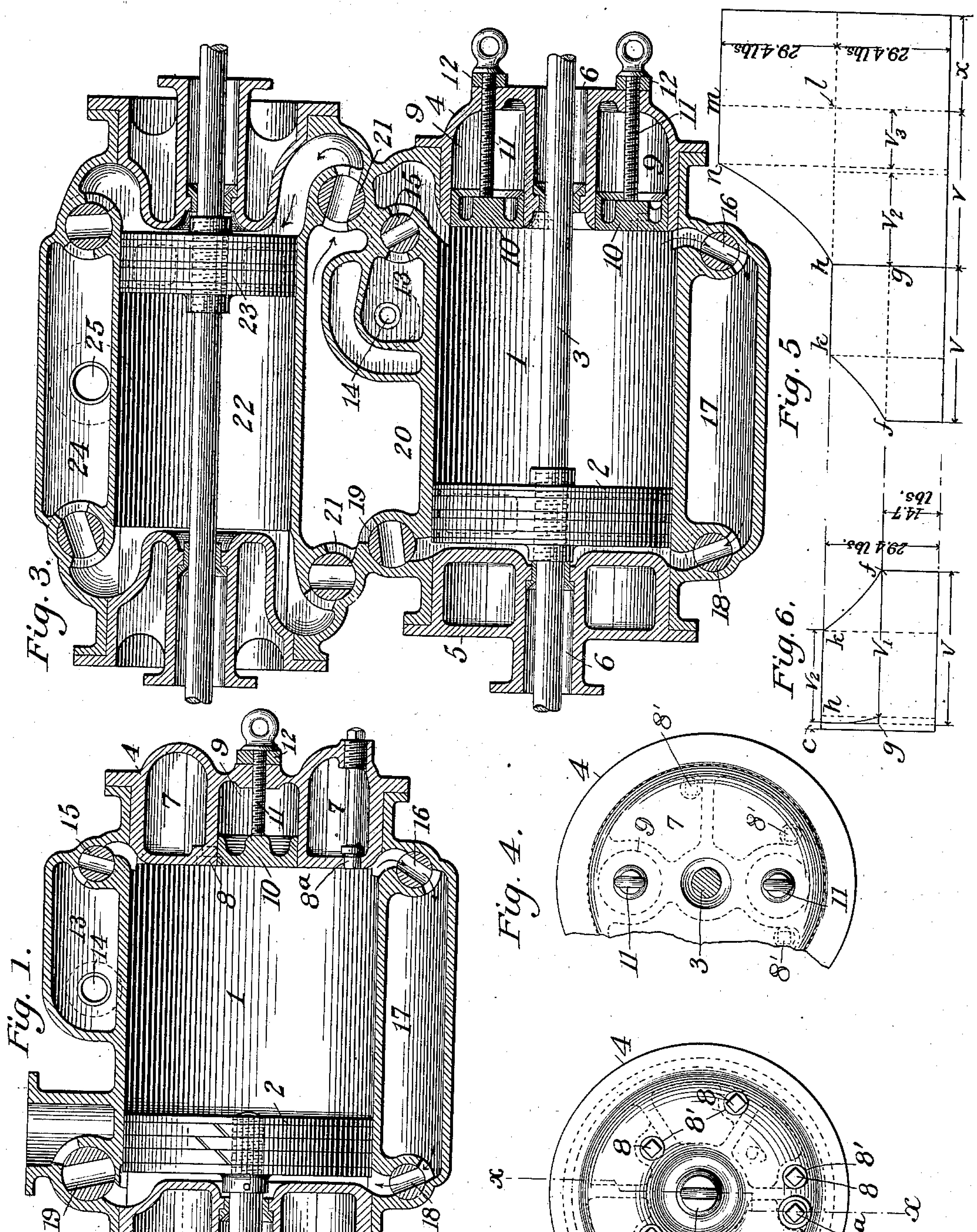
L. ALLEN.

APPARATUS FOR EXPANDING AND COMPRESSING GASES.

(Application filed Mar. 28, 1899.)

(No Model.)



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APPARATUS FOR EXPANDING AND COMPRESSING GASES.

SPECIFICATION forming part of Letters Patent No. 661,784, dated November 13, 1900.

Application filed March 28, 1899. Serial No. 710,853. (No model.)

To all whom it may concern:

Be it known that I, LEICESTER ALLEN, of the borough of Bronx, city of New York, and State of New York, have invented an Improved Apparatus for Expanding and Compressing Gases and Vapors for Use in Refrigeration and for other Purposes; and I do hereby declare the following to be a full, clear, and exact description of my invention, reference being had to the accompanying drawings, forming part of this specification.

My invention partly relates to means for effecting that kind of expansion or compression known in the art as "stage" expansion or compression and in which the gas or vapor is not expanded or compressed by one continuous expansion or by one continuous compression, but in which the gas or vapor is expanded or compressed in and by separate and consecutive operations to different pressures or "stages" of expansion or compression either with or without intermediate heating or cooling, such intermediate heating or cooling when used being ordinarily effected by passing the gas or vapor after partial expansion or compression through a heating or cooling medium or over a heated or cooled surface.

Hitherto different stages of expansion or compression have been for the most part attained in separate expansion-engine cylinders or compression-engine cylinders by the reciprocation of a piston therein, the volumes of gas or vapor admitted to and discharged from such cylinders being controlled either by automatic or positively-actuated valves or in some instances by both positively-actuated and automatic valves.

My invention partly relates to the cylinders and heads of cylinders of engines used in the expansion and compression of gases and vapors, which engine-cylinders and engines may at will be employed either for expansion or compression.

My invention also relates to certain combinations of one or more cylinders comprising my improvements with an engine-cylinder of a hitherto commonly used type for a purpose hereinafter specified.

In an apparatus embodying my invention the volumes and pressures of gases or vapors are changed in stages in an engine-cylinder having a reciprocating piston and equal and uniform stroke displacement and having a larger clearance connected with the high-pressure space than that connected with the low-pressure space therein, the clearance connected with the low-pressure space being chosen arbitrarily and the clearance connected with the high-pressure space being a mathematical function of the clearance connected with the low-pressure space and computed therefrom, as hereinafter set forth, the function of said apparatus specifically consisting in inducting to such a cylinder on one side of said piston the volume of gas or vapor which it is desired to change to another specific pressure and volume, effecting a part of such change during the completion of the stroke of the piston after the said induction, exhausting or discharging the so partially changed volume from the cylinder and from the space therein on that side of the piston wherein the partial change has been effected, inducting the so exhausted or discharged volume to the space on the other side of said piston, and there effecting still another change of pressure and volume during the movement of the piston in a direction opposite to that by which the first change of volume and pressure was effected, substantially as hereinafter more fully set forth.

The apparatus may be used solely and separately for effecting a given total change of pressure and volume of a gas or vapor, or it may be used in combination with previously-employed methods.

My improved apparatus consists, partly, in an engine-cylinder for expanding or compressing gases or vapors into which predetermined different volumes but equal weights of a gas or vapor are respectively inducted on opposite sides of a piston reciprocating in said cylinder, the end clearance connected with the low-pressure space of which is chosen arbitrarily by its designer or constructor, while the end clearance on the high-pressure side of said piston is made larger and its content computed as a mathematical function of the arbitrarily-assumed clearance on the low-pressure side, as hereinafter described, the high-pressure space and the low-pressure space separated by said piston being connected by a valve-controlled passage.

My invention also partly consists of means whereby the end clearance on the high-pressure side of the piston of such an engine-cylinder may be so readily and easily and closely adjusted to the required mathematical function of the end clearance on the low-pressure side as to meet all practical requirements without removal of the head of such cylinder.

For purposes of this specification I will use the term "engine-cylinder" as including its heads, valve-chests, valves, and generally all its appurtenances except the piston and piston-rod and the heat-insulating material or materials with which it may be enveloped. I will also use the term "end clearance" to indicate all the continuous space or volume which at the beginning of the stroke of the piston is comprised in and included by the cavities connected directly or indirectly with the space lying between the piston and the cylinder-head nearest to the piston. I will also employ the term "stroke displacement" to indicate a volume of gas or vapor displaced by the movement of the piston from the body of the cylinder or its interior or a geometrical volume equal to the volume described by the advancing face of the piston during a single stroke. I also mean by the words "equal stroke displacement" such substantially equal stroke displacement as is commonly effected in double-acting reciprocating engines having ordinarily-used sizes of piston-rods, the volume of the piston-rod itself being so small in comparison with the volume described during the stroke by the advancing free face of the piston opposite that face which is directly adjacent to the piston-rod as usually to produce an inequality not exceeding from three to four per cent. of the volume described by said free face. I will also use the term "valve-controlled passage" to indicate a passage or duct for the induction or eduction of gas or vapor into or out of the body of the cylinder, or both into or out of the same, the time and quantity of such induction or eduction being regulated by any kind of valve familiar to engineers or which may be hereafter produced. I will also distinguish the spaces in an engine-cylinder situated on opposite sides of a reciprocating piston, to one of which a gas or vapor is inducted at higher pressure than the gas or vapor is inducted to the other, respectively, as the "high-pressure" space and the "low-pressure" space, the term "high-pressure" space meaning the space to which the gas or vapor at the higher pressure is inducted and the term "low-pressure" space meaning the space into which the gas or vapor is inducted at a lower pressure. The said high-pressure space and low-pressure space are each considered herein as exclusive of the end-clearance space and at their maximum each equal to the stroke displacement. They may therefore be properly characterized as an "inclosed variable high-pressure space" and an "equal inclosed variable low-pressure space" separated from each other by a movable septum. The septum may be either a piston or a flexible diaphragm; but for purposes of this specification it will be described as a piston.

In this specification I will also hereinafter use the word "gas" as inclusive in its meaning of all vapors or mixtures of gases or vapors or mixtures of the same with some percentage of the liquids from which they are generated.

Figure 1 in the drawings illustrates the construction of a single engine-cylinder and its heads as used by me in my invention for carrying out two separate stages of expansion or compression, the drawing being a section taken on the line $x\,x$ in Fig. 2. Fig. 2 is a partial detailed view of the inside of one of the heads of the cylinder shown in Fig. 1, showing novel features of construction which are a part of my invention. Fig. 3 is a vertical section through an engine-cylinder constructed similarly to that shown in Fig. 1, but having a somewhat-modified form of head and through another engine of ordinary type, the two cylinders being combined in such manner as to carry out three separate stages of expansion or compression. Fig. 4 is a partial outside view of the modified form of cylinder-head just mentioned above. Figs. 5 and 6 are diagrams used to illustrate the nature and results attained by my improved apparatus. They are of the nature of diagrams obtained by the use of the well-known steam-indicator; but making no allowance for losses by friction or heat interchanges they approximately indicate only theoretical results rather than the actual results which are attained in practice.

Referring now to drawings, Figs. 1 and 3, the cylinder in each, wherein two separate and distinct expansions or compressions of the same weight of gas may be performed, is numbered 1 in Figs. 1 and 3, the high-pressure space in each of these cylinders being shown as at the right of the piston and the piston being shown as having just completed its stroke displacement. In these figures the pistons of the cylinders 1 are indicated by the numeral 2, the piston-rods by 3, those cylinder-heads which comprise a part of my invention by 4, those heads which do not comprise any part of my invention by 5, and the stuffing-boxes by 6. The piston-rod 3 is in practice connected by intermediate mechanism with the crank of a fly-wheel shaft, which by stored energy will move the piston during transfer of gas from either of the spaces to the space on the other side of the piston and will also regulate the movement of the piston during other periods of the stroke; but as a fly-wheel and the connections of the same to the piston-rod constitute no part of my invention they are omitted in the drawings, and as they are old and familiar devices in the art it is unnecessary to further describe them.

Each of the "cylinders"—in which term, as above explained, the heads of the cylinders are included—has different end clearances, that end clearance connected with the high-pressure space being greater than that connected with the low-pressure space, but being at the same time a function of that connected with the low-pressure space. This relation between the end clearances of the cylinders, in which two stages of expansion or compression are performed, is essential to the accurate operation of the apparatus, and the clearance connected with the low-pressure space being arbitrarily assumed the clearance connected with the high-pressure space is accurately computed by the formula given below, wherein the clearances are expressed as fractions or percentages of the stroke displacement and the stroke displacement is taken as a unit of volume. The formula for computing the clearance on the high-pressure side is derived from the following algebraic equations, which also supply the needed formulæ for determining in advance the points of cut-off and of exhaust opening and closure.

The notation used in the formulæ and the equations which follow is considered as being for expansion of gases and vapors; but when the apparatus is used for compression the clearance connected with the high-pressure space is the same as when it is used for expansion and is computed precisely as though the apparatus were to be used solely for expansion. When the ratio of compression in the low-pressure space is the reciprocal of that employed in expansion, the volume inducted to the low-pressure space for compression will be exactly the same as the volume discharged from the same space after final expansion.

Notation.

v equals the stroke displacement, (represented in the diagrams, Figs. 6 and 7, by abscissas v,) the stroke displacement being taken as the unit of volume.

v_1 equals the volume delivered from the low-pressure space after the second stage of expansion has been performed.

v_2 equals the volume inducted to the low-pressure space, and consequently the volume delivered from the high-pressure space after the first partial expansion.

v_3 equals the volume inducted to the high-pressure space before the first stage of expansion.

C equals the arbitrary clearance connected with the low-pressure space and expressed as a fraction of the stroke displacement v. This arbitrary clearance should be the minimum practically possible to attain best results.

x equals the clearance connected with the high-pressure space, also expressed as a fraction of the stroke displacement v and to be computed for each case.

$p_3\ p_2\ p_1$ equal respective symbols for high, intermediate, and lowest pressures in the order named.

R_1 equals the ratio v_2/v_1, corresponding to the ratio p_1/p_2 and found for air by the formula $p_1v_1^k=p_2v_2^k$ or found for steam by the formula $p_1v_1^m=p_2v_2^m$, the value of k for air being 1.41, and the value of m for saturated steam containing no water when inducted being 1.134, which is a mean value for different pressures.

R_2 equals the ratio v_3/v_2, corresponding to the ratio p_2/p_3 and computed in the same way as directed for R_1.

The stroke displacement being taken as unit of volume and the clearance represented by C, the entire contents of the low-pressure space, together with the clearance connected therewith, is equal to $1+C$. The exhaust closure is effected, as hereinafter explained, at a point of the stroke such that the gas retained in the cylinder by the closure will at the completion of the stroke be compressed in the clearance in the ratio R_1 or to a pressure substantially equal to the maximum pressure in said space. Consequently the volume v_1 that will be delivered from the low-pressure space will be the entire volume $1+C$ less R_1C. From this reasoning is derived Equation 1.

We may write the following equations:

$$v_1=1+C-R_1C \ \ldots\ldots\ldots\ldots \ (1)$$
$$v_2=(1+C-R_1C)\div R_1 \ \ldots\ldots \ (2)$$
$$v_3=(1+C-R_1C)\div R_1R_2 \ \ldots\ldots \ (3)$$
$$x=(1-v_2)\div(R_2-1) \ \ldots\ldots \ (4)$$

As the volume v_1 delivered from the low-pressure space is equal to the inducted volume v_2 multiplied by the ratio R_1, we find v_2 by simply dividing the volume $v_1=1+C-R_1C$ by R_1, and thus we derive Equation 2, which expresses the value v_2 or the volume inducted to the low-pressure space, which is of course also the volume discharged from the high-pressure space, and as this volume v_2 is equal to the volume inducted to the high-pressure space multiplied by the ratio R_2 (which is the ratio of expansion in the high-pressure space) the volume v_3 will be the volume $(1+C-R_1C)\div R_1R_2$, and thus we derive Equation 3. Lastly, x representing the clearness on the high-pressure side it is clear that the stroke displacement plus this clearance is the total volume of the high-pressure space, together with the clearance connected therewith, and as $1-v_2+x$ equals the volume that must remain in the high-pressure space and the clearance x, connected therewith, and as in order that this shall fill the clearance space at the highest pressure it must be compressed to the volume

$$(1-v_2+x)\div R_2,$$

we have

$$x=(1-v_2+x)\div R_2.$$

Hence

$$R_2x=1-v_2+x.$$

Hence

$$(R_2-1)x=1-v_2.$$

Hence

$$x=(1-v_2)\div(R_2-1),$$

which shows the derivation of Equation 4.

Equations 1, 2, and 3 show that the volumes v_1, v_2, and v_3 are functions of the arbitrary clearance assumed for the low-pressure space, and equation 4 shows that the clearance connected with the high-pressure space is a function of v_2, which being a function of C, x is also a function of C. The values of v_1, v_2, and v_3 having been found in terms of stroke displacement, if the latter be represented by an abscissa having a length equal to the length of the stroke drawn to any convenient scale the said values become formulæ for determining the points of cut-off, exhaust opening and closure, &c.

When the ratio of the change of pressure effected in the machine is comparatively small and is also alike in both the high and low pressure spaces, the clearance connected with the high-pressure space is large in proportion to the stroke displacement, even when the arbitrary clearance connected with the low-pressure space is a small fraction of the stroke displacement; but with the arbitrary clearance connected with the low-pressure space remaining constant the clearance connected with the high-pressure space requires to be smaller as the ratios of change of pressures increase and also when the ratio of pressure change in the high-pressure space is less than that in the low-pressure space. When $p_1/p_2=4$ and $p_2/p_3=2$ and the arbitrary clearance is four per cent. of the stroke displacement, the clearance connected with the high-pressure space is found by the formula given to be about sixteen per cent. of the stroke displacement. When $p_1/p_2=6$ and $p_2/p_3=3$ and the arbitrary clearance is four per cent. of the stroke displacement, the clearance connected with the high-pressure space requires to be about seventeen per cent.

When intermediate heating or cooling is employed, the value of k or of m in the formula for finding the relative pressures and volumes increases or diminishes by an amount corresponding to the temperature change so effected. The temperatures respectively taken before and after such heat change is effected are the additional data needed for determining the relative pressures and volumes by the use of thermodynamic formula familiar to engineers.

The formulæ given are based on the assumptions that the expansion or compression is adiabatic and that there is no heating or cooling of the expanded or compressed gas between the stages of compression or expansion during passage of the gas or vapor from the high-pressure space to and into the low-pressure space. If intermediate heating or cooling is employed, the values of k and of m will be more or less modified for the inducted volumes, the extent of such modification being determined from the resulting temperatures so produced.

In order that a machine of this kind having a given stroke displacement and given arbitrary clearance connected with the low-pressure space may be readily employed for different pressure ranges of expansion or compression, it is obvious that means of conveniently changing the volume of the clearance connected with the high-pressure space, preferably without removing the heads, must be provided. Such means are supplied in my invention, and as I believe myself to be the first to provide such means I desire to secure this feature broadly, not rigidly confining myself to the precise mechanism or either of the two modifications of mechanism for this purpose which I will now proceed to describe.

In each of the heads 4, which, with the bodies of the cylinders to which they are fitted and pistons working in said cylinders, inclose the high-pressure spaces I form chambers 7 of fixed capacity, these chambers being partly shown in section in Fig. 1 and in dotted outline in Figs. 1, 2, and 4. There are six of these chambers in the example of a two-stage expansion or compression cylinder shown in Fig. 1 and four in the two-stage expansion or compression cylinder shown in Fig. 3. The number of these chambers should be sufficient to enable the clearance connected with the high-pressure space to be adjusted, as hereinafter described, to any percentage of the stroke displacement between the minimum and maximum percentage of clearance for which the machine is designed. Thus if the minimum clearance connected with the high-pressure space which the machine is designed to have—that is to say, the volume contained between the piston at the end of the stroke toward the said head plus the volume contained in the ports between the valves and the piston on the same side—is eight per cent. of the stroke displacement and the maximum clearance on the same side for which the machine is designed is sixty-two per cent. there must be enough of these chambers when used in conjunction with another feature of construction described farther on to permit adjustment of the clearance to any percentage or fraction of the stroke displacement between said maximum and minimum.

Each of the chambers 7 is provided with a hole 8, placed as nearly as practicable at the lower part of said chamber. When this hole is opened, the volume contained by the chamber is added to the previously-existing clearance. When the hole is closed, the same volume is subtracted from the previously-existing clearance. These holes may be closed or opened by inserting into them or taking out from them screw-plugs 8'; but I prefer to provide for closing or opening them by supplying each with a screw-valve 8^a, Fig. 1, which has its threaded portion in the exterior shell of the head and a squared end extending out from the shell, which end may be engaged by an ordinary wrench or spanner. The inner end of the valve is fitted to the hole by grinding or packing to make it gas-tight. As these valves are in general to be rarely used, the construction described is preferred on account of its cheapness; but it is obvious that a screw-valve constructed in a manner analogous to the ordinary globe-valve and having a packed stem may be substituted in a machine desired to frequently change its range of pressures in the high-pressure space. When screw-valves 8^a are used and when they are taken out, the screw-holes in the outer shell of the head are stopped with a screw-plug, a portion of the thread into which the screw-plug is fitted having a tapered thread, as in the ordinary manner of plugging a hole gas-tight in metal.

If the minimum normal clearance be ten per cent. and the maximum clearance designed for the high-pressure space be sixty per cent. of the stroke displacement, the chambers 7 in a single head may together contain a volume equal to fifty-four per cent. of such stroke displacement. If there be six of these chambers of substantially equal capacity, as shown in Fig. 1, they would, on the above assumption, if of equal capacity, each contain, approximately, nine per cent. of the stroke displacement. This would alone permit adjustment to seven different clearances—to wit, the normal minimum of ten per cent.—with six additions of substantially nine per cent. each. It is, however, difficult to core out a casting with such precision as to give complete accuracy to these fractional clearances, and it is, moreover, necessary to provide for all intermediate fractional clearances in order to carry out the operation of the apparatus for different stages of compression or expansion in one and the same apparatus and with assured results. I therefore provide each cylinder-head adjacent to a high-pressure space with an additional device for this purpose. I construct in each of said heads one or more cylinders 9, Figs. 1, 2, and 3, ground or bored on the interior to accurate cylindrical form, and I fit in each, accurately and gas-tight, a movable piston-plug 10. Such piston-plug is forced toward the high-pressure space in the body of the cylinder and held in position in one direction by a screw 11, which passes through a threaded hole in the exterior shell of the head, as shown in Figs. 1, 2, 3, and 4. As the piston is gas-tight, the screw 11 is not required to fit perfectly tight. It needs to be a good working fit, however, and it may be held from moving after adjustment by a jam-nut 12. The outer end of the screw may be formed with an eye, as shown, by which means it may be turned for adjustment, and which also affords a convenient attachment for the hook of a tackle when removing the head. The piston-plug will be pressed firmly against the inner end of the screw in any position of the latter by the pressure of the gas in the high-pressure space of the cylinder. I prefer to make the axes of these cylinders parallel to the axes of the engine-cylinders 1; but this requirement is by no means essential. There may be more than one of these cylinders and plug-pistons in a cylinder-head, as shown in Fig. 3. The capacity of such cylinder when there is only one should be, preferably, a little more than the calculated capacity of one of the chambers 7, or if more than one of them be employed their combined capacity when the piston-plug is pressed out by the gas in the cylinder as far as the construction will permit should be, preferably, a little more than the calculated capacity of a single chamber 7.

It is evident that by the adjustment of the regulating screw or screws 11 the clearance can be increased by any desired fraction of the capacity of the piston-plugged cylinder or cylinders 9. By the employment of these cylinders and their pistons in conjunction with the chambers 7 a clearance which is any desired fraction of the stroke displacement within the maximum and minimum limits of clearance for which the machine is designed may be secured. This adjustment of the clearance serves also another useful purpose. In a heat-engine which converts heat into work by expanding gaseous bodies and applying the work exteriorly to the expanding body a clearance space which is connected with the space in an outer exhaust-port is a source of loss of work, because during the exhaust the metal inclosing the clearance cools and imparts heat to the outflowing gaseous body, which heat cannot thereafter be directly recovered and again applied to work; but in a compound, triple, or quadruple expansion engine having only one outer exhaust the exhaust from the cylinder or cylinders carrying the higher pressure leads to the induction-ports of those carrying lower pressures. Therefore although the metal inclosing clearance connected with a high-pressure space imparts heat to the outflowing gaseous body in the same way as it does to a finally exhausted gas this heat is not wasted, because it increases the pressure or volume of the gas inducted to the next cylinder, where its expansive force is again exerted. This fact causes the compound or multiple expansion system to utilize more of the expansive force of the primarily-contained heat than can be utilized in a single-expansion engine. As yet the exact amount of heat that is transferred from the metal inclosing the clearance during exhaust and from the metal of the body of the cylinder during the exhaust period has not been expressed in mathematical formulæ convenient and available for general use in designing engines, and hence to obtain the greatest exactness in the operation of such engines it may be necessary to alter the clearances as well as the valve-setting. Such adjustment and alteration of clearances may be readily effected by the employment of my invention herein described.

In the operation of the apparatus the heat given off to the outflowing gaseous bodies from the metal inclosing the high-pressure spaces is utilized in the spaces having lower pressure in the same way as in ordinary multiple expansion.

In Fig. 1 I have illustrated a double expansion or compression engine-cylinder. When used for expansion, the gas to be expanded is first inducted to the high-pressure chamber or chest 13 through the opening 14, thence it passes through the induction-valve 15 into the cylinder 1, and the admission being cut off by the said valve when the proper volume has been admitted it thereafter expands behind the advancing piston till the latter has completed its stroke. The eduction-valve 16 then opens and the gas, having expanded through its first stage, enters the valve-controlled duct or passage 17, which leads to the low-pressure space on the other side of the piston, the valve 18 performing the function of an induction-valve and cut-off. As soon as a volume equal to that discharged from the high-pressure space has entered the low-pressure space a cut-off is effected by the closure of the valve 18. Thereafter the inducted gas expands through another stage, thus causing the work of the expansion to be exerted upon the moving piston, and when this expansion is complete the exhaust-valve 19 opens and allows the gas now expanded through two stages to pass out. These operations continuously succeed each other in the regular working of the engine, the power developed being applied, through the reciprocating piston-rod and its connection to the performance of exterior work. The exhaust closure in each of the high and low pressure spaces is made at a point such as will retain in the cylinder sufficient gas to fill the clearance connected with such space with gas substantially at the highest pressure realized therein. The heat which passes from the metal inclosing the clearance into the gas or vapor during the exhaust is thus restored to the metal before any more gas is inducted, so that in case a liquefiable gas is used there will not be any material initial condensation in the clearances, and if, as is usual, the cylinder and its heads be covered with a substance which much resists the passage of heat there will be only a very minute loss through the inclosing metal. Each of the cylinders 1, Figs. 1 and 3, operates for expansion in the same manner, the induction and eduction valves being indicated by the same numbers used in the same order as those by which the valves in Fig. 1 are indicated.

When the same cylinders are used for compression, the gas is inducted to each of them, primarily, at and through the valve 19, and its course through any one of the said cylinders is exactly the reverse of that described for expansion, its final issue from the cylinder being through the valve 15 into the chest 13 and out through the opening 14. In this case the gas instead of performing exterior work through the medium of the piston-rod has work performed upon it by exterior power applied to the piston-rod, and the valve-gear and valves must be adjusted to open the valves at the same place where they close for expansion and close at the same place where they would open for expansion.

When the machine is used for a compressor, a volume substantially equal to that of the stroke displacement is inducted to the low-pressure space, the induction-valve being then closed. The piston, which has now made a full stroke, makes a return stroke, compressing the confined gas to the first stage. Thereupon the discharge-valve on the low-pressure side of the piston and the induction-valve on the high-pressure side open simultaneously and the gas compressed to its first stage is transferred by the remainder of the stroke to the high-pressure space through the valve-controlled passage. The gas having been so transferred both the discharge-valve of the low-pressure side and the induction-valve of the high-pressure side are closed, and the discharge-valve of the high-pressure side remains closed. The piston then makes a third stroke, again inducting a volume substantially equal to the stroke displacement into the low-pressure space, and at the same time compressing the volume confined in the high-pressure space. When the piston in this stroke reaches the point fixed for discharge from the high-pressure space, the discharge-valve of the high-pressure space is opened and all the gas is expelled from that side except what fills the end clearance. This series of actions being repeated indefinitely the transferred compressed gas discharged into and confined in a receiver such as is commonly used with air-compressors to retain the compressed gas soon arrives at the maximum pressure, the machine becomes fully charged, and thereafter it works normally, as hereinafter described. The theoretical work consumed in one stroke by the compression of air in this manner from a given absolute pressure to a stated higher pressure and its discharge from the cylinder is diagrammatically represented in Figs. 5 and 6, the lowest pressure being one and the highest pressure being four atmospheres, the stroke displacement being a unit of volume, the compression being performed in two stages, and the intermediate pressure at the end of the first stage being two atmospheres. In Fig. 6 the line v represents the stroke displacement of the piston; c, the arbitrary clearance connected with the low-pressure space; v', the volume inducted to the low-pressure space; v^2, the volume discharged, and the area $f\,g\,h\,k$ the work expended in compressing the volume v' to the volume v^2 and discharging the latter from the low-pressure space into the passage which leads to the high-pressure space. In Fig. 5 the line v represents the stroke displacement; x, the clearance connected with the high-pressure space and computed as herein specified; v^2, the volume discharged from the low-pressure space, which is also the volume inducted to the high-pressure space; v^3, the volume discharged after the second stage of compression, and the area $h\ l\ m\ n$ the work expended in making the final stage of compression and in effecting the discharge of the changed volume out of the cylinder. The sum of these two areas $f\ g\ h\ k$ and $h\ l\ m\ n$ represents the total work of compressing the volume v' adiabatically under the specified conditions. In practice of course the work of overcoming the passive resistances of frictions would be added to the amount of the work represented. The total theoretical exterior work performed in expanding a volume v^3 down to one atmosphere from four atmospheres is also indicated by the sum of the areas $f\ g\ h\ k$ and $h\ l\ m\ n$.

Stage expansion or compression may also be partly carried out in a cylinder constructed as I have described and partly in an ordinary single expansion or compression engine. An example of such construction is shown in Fig. 3. In this arrangement the cylinder 1 is the high-pressure cylinder, constructed, as hereinbefore described, with clearance-chambers 7 in the head 4. In expanding the gas exhausts from the low-pressure space of the cylinder 1 through the valve 19 into the chest 20. Thence it is alternately inducted to the ordinary double-acting engine-cylinder 22 through the valves 21, expanding equally on both sides of the piston 23, exhausting into the common exhaust-chamber 22, and finally passing out at the opening 25. This arrangement provides a means of compressing or expanding through three stages in two cylinders when the operation is carried out in one of said cylinders. In this case the low-pressure cylinder may sometimes be smaller than the high-pressure cylinder when the ratio of change of pressure and volume in the high-pressure cylinder is small as compared with the ratio of such change in the low-pressure cylinder.

By arranging two engine-cylinders constructed in accordance with my invention in such manner that their piston-rods coöperate with a single fly-wheel shaft and so that the low-pressure space of the cylinder inducting at higher pressure exhausts into the high-pressure space of the cylinder inducting at a lower pressure I can effect a quadruple stage expansion with said two cylinders.

By the use of three cylinders constructed in accordance with my invention and similarly connected I effect a sextuple compression or expansion. By the use of two such cylinders and one of the ordinary type I can effect a quintuple compression or expansion.

What I claim as my invention is—

1. As a means for changing, in different stages, the volume and pressure of a gas or vapor, an engine-cylinder containing a reciprocating piston and having equal piston displacement in both a high-pressure space on one side of the piston and a low-pressure space on the opposite side of the piston, the said cylinder having an end clearance connected with its high-pressure space larger than that connected with its low-pressure space, said high and low pressure spaces having between them a connecting-passage and said larger end clearance being a mathematical function of the end clearance connected with said low-pressure space and computable therefrom, substantially as and for the purposes specified.

2. As a means for changing in stages the volume and pressure of a gas or vapor, the combination with an engine-cylinder containing a reciprocating piston and having equal piston displacement in both a high-pressure space on one side of the piston and a low-pressure space on the opposite side thereof and an end clearance connected with its high-pressure space larger than that connected with its low-pressure space, said high and low pressure spaces having between them a connecting-passage and said larger end clearance being a mathematical function of the clearance connected with said low-pressure space and computable therefrom substantially as described, of means for varying the said larger end clearance independently of the position of the cylinder-head adjacent to said high-pressure space, substantially as and for the purposes described.

3. The combination with an engine-cylinder containing a reciprocating piston and having a uniform piston displacement in both a high-pressure space on one side of the piston and a low-pressure space on the opposite side of the piston, the said cylinder having an end clearance connected with the high-pressure space larger than that connected with the low-pressure space, said high and low pressure spaces having between them a valve-controlled connecting-passage, of means for varying end clearance independently of the position of the cylinder-head adjacent to said clearance, substantially as herein described.

4. As a means for changing in stages the volume and pressure of a gas or vapor, the combination with an engine-cylinder containing a reciprocating piston that has equal piston displacement in both a high-pressure space on one side of the piston and a low-pressure space on the opposite side of the piston, the said cylinder having an end clearance connected with its high-pressure space larger than that connected with the low-pressure-space, said high and low pressure spaces having between them a connecting-passage and said larger end clearance being a mathematical function of that connected with said low-pressure space and computable therefrom substantially as described, of means for varying and adjusting the volume of said larger end clearance to any fraction of the stroke displacement within the limits of maximum and minimum end clearance for which said cylinder is designed, substantially as and for the purposes set forth.

5. As a means for changing, in different

stages, the volume and pressure of a gas or vapor, an engine-cylinder containing a reciprocating piston and having equal piston displacement in both a high-pressure space on one side of the piston and a low-pressure space on the opposite side of the piston, the said cylinder having an end clearance connected with its high-pressure space larger than that connected with its low-pressure space, said high-pressure and low-pressure spaces being connected with each other by a valve-controlled passage, substantially as and for the purposes specified.

Signed at New York, in the county of New York and State of New York, this 23d day of March, A. D. 1899.

LEICESTER ALLEN.

Witnesses:
A. M. ALLEN,
MRS. E. NEWTON.