

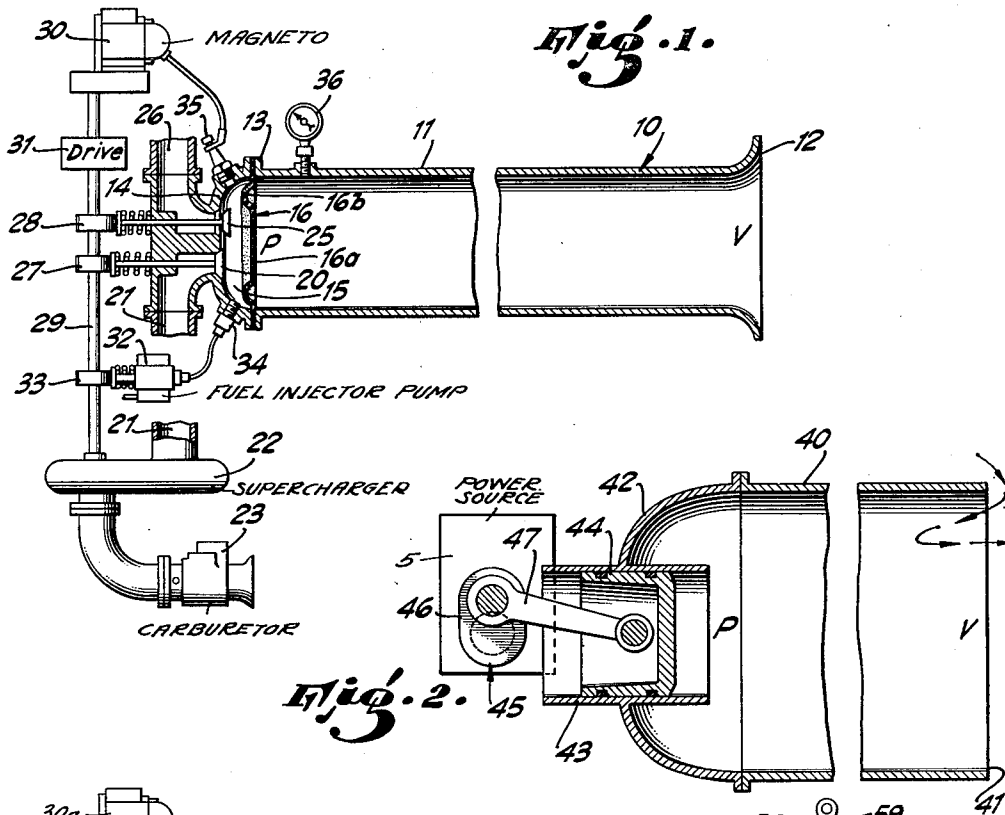
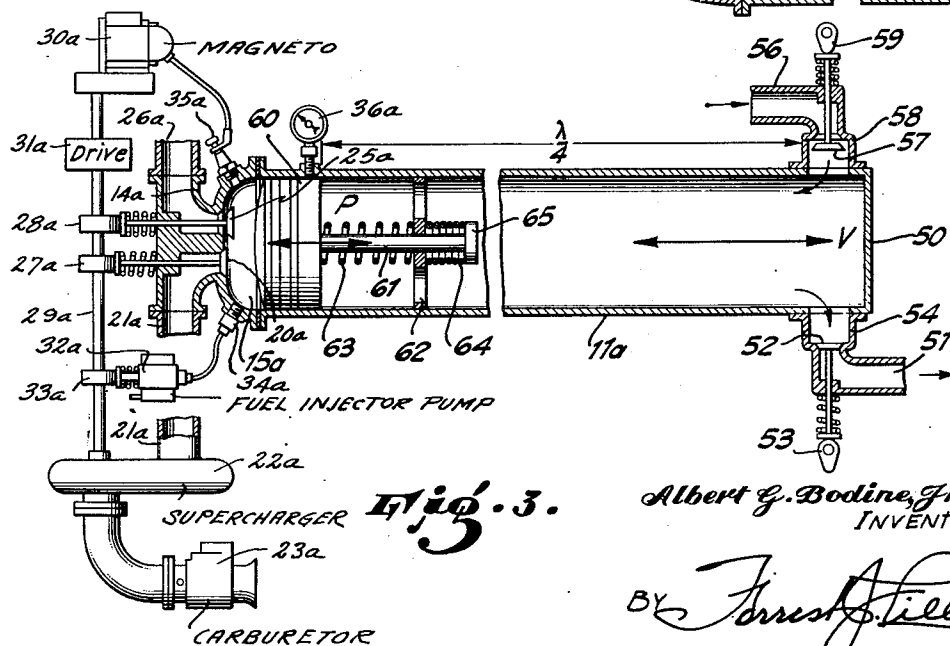
April 3, 1951

A. G. BODINE, JR
PULSE JET STANDING WAVE ENGINE WITH MOVABLE
WAVE REFLECTING MEANS

2,546,965

Filed June 11, 1947

3 Sheets-Sheet 1



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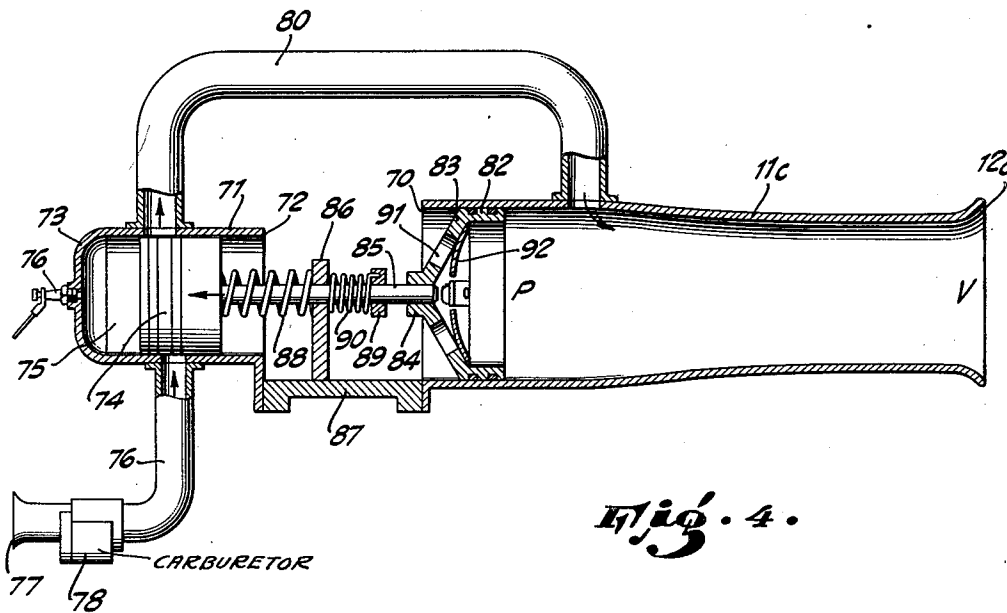
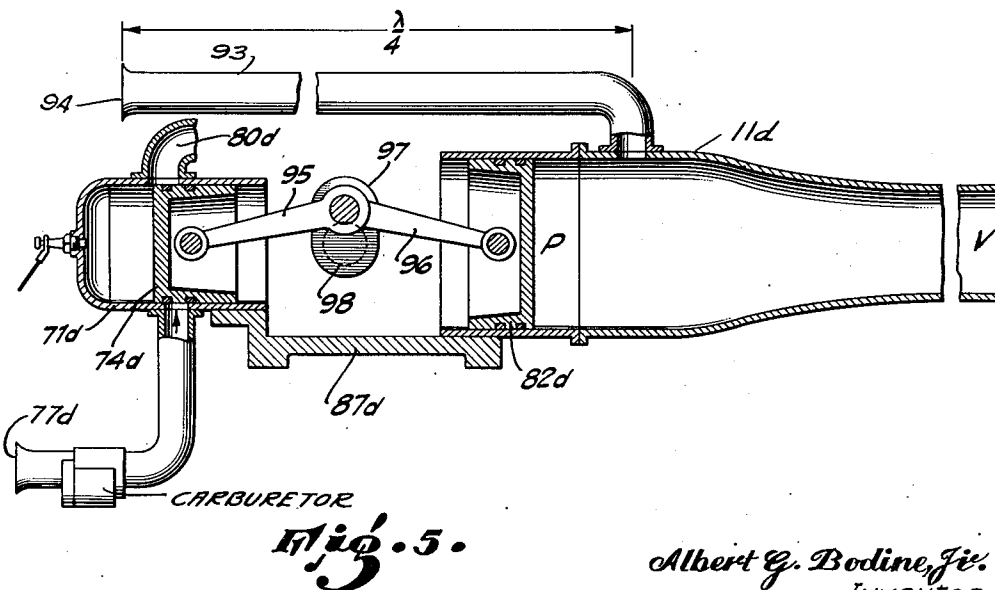
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3 Sheets-Sheet 3

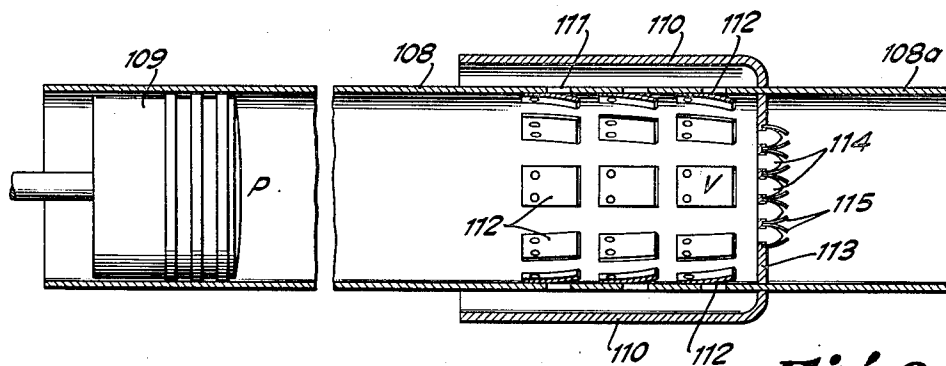


Fig. 6.

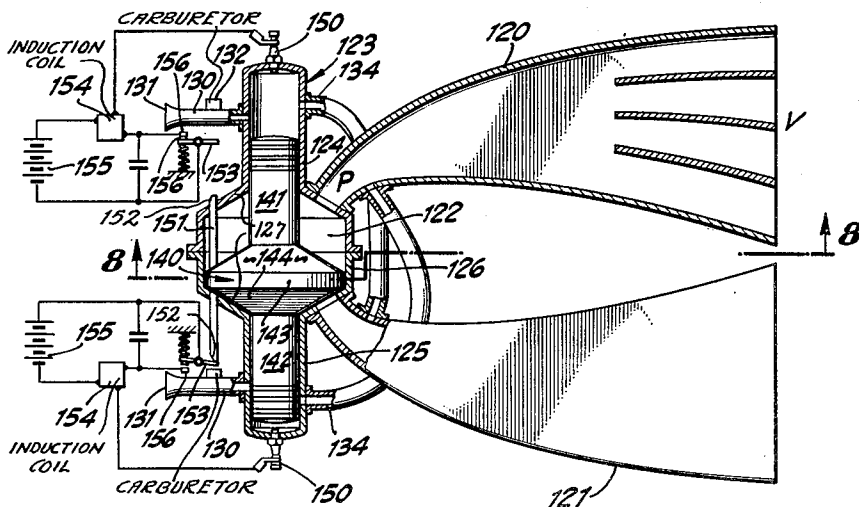


Fig. 7.

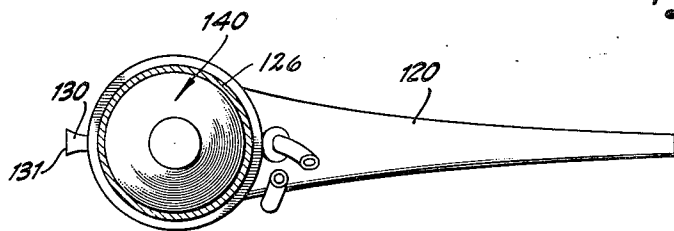


Fig. 8.

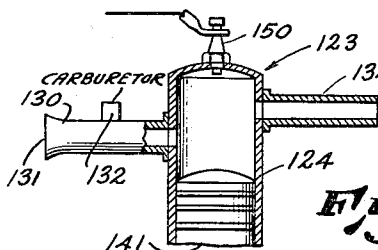


Fig. 9.

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UNITED STATES PATENT OFFICE

2,546,965

PULSE JET STANDING WAVE ENGINE WITH
MOVABLE WAVE REFLECTING MEANS

Albert G. Bodine, Jr., Van Nuys, Calif.

Application June 11, 1947, Serial No. 753,898

17 Claims. (Cl. 60—35.56)

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This invention relates generally to jet engines, and more particularly and illustratively to thermal jet engines of the acoustic standing wave type employing the principles of acoustic wave radiation pressure as set forth in my copending prior application entitled Method and Apparatus for Generating a Controlled Thrust, Serial No. 439,926, filed April 21, 1942, now abandoned, of which the present application is a continuation-in-part. See also my Patent No. 2,480,626, filed November 3, 1947, as a continuation-in-part of and substitution for said application Serial No. 439,926.

Jet engines of the class to which the present invention belongs have their primary present application in the field of jet propulsion. They are, however, not restricted to such use, and may equally well be employed as blowers, pumps, or compressors. Accordingly, while the present invention is, for simplicity, disclosed herein in forms primarily intended for jet propulsion, and with jet propulsion chiefly in view, no limitation thereto is to be implied.

Thermal jet engines of a certain type disclosed in my said copending application employ a tubular housing having a closed end portion that houses a fuel combustion zone, and having an opening at the opposite end through which gaseous products of combustion are discharged. Fuel combustion is effected intermittently, at a resonant frequency of the tubular housing, so that a standing wave is established in the latter, with a pressure anti-node at the combustion zone and a velocity anti-node at the open end. If the tubular housing is of substantially uniform cross-sectional area throughout, it behaves acoustically as a quarter-wave organ pipe.

It will be noted that the combustion zone in such an apparatus desirably coincides with the pressure anti-node region, where the acoustic impedance of the apparatus (pressure amplitude divided by gas particle velocity) is at its optimum value. This is an advantageous arrangement, since explosive type fuel combustion in a semi-closed chamber is a phenomenon having pressure versus displacement characteristics analogous to relatively high acoustic impedance, and in order to induce substantial transfer of power from the flame to the gas column, the impedance of the latter must be matched to that of the explosion (or at least be made to approach as nearly as possible the impedance of the explosion). Such an engine in its simple form has certain disabilities which it is the general purpose of the present invention to overcome.

I have found, for instance, that the column of combustion gases in such an apparatus has a much lower acoustical impedance (the standing wave disregarded) than a similar column of clean

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air. This condition obviously augments the mismatch between combustion impedance and gas column impedance, with attendant reduction in the energy that can be transferred to the gas column. Furthermore, foreign matter such as soot and complex chemicals of combustion products in the air column introduces frictional resistance, meaning general power loss, as well as reduced "Q," with resulting attenuation of the all important standing wave.

A further disadvantage in the previously known jet engine of the simple type described has been the impossibility of achieving high compression and expansion ratios, such engines having heretofore been limited to a ratio of substantially 2 to 1. This, of course, leaves room for substantial improvement if reasonable fuel economy is to be achieved.

Objects of the invention include the provision of a thermal jet engine of improved thermal cycle giving greatly improved power and improved fuel economy, and particularly one capable of relatively high compression and expansion ratio. In this connection, a further object is the provision of a thermal jet engine in which the thermal compression ratio is independent of wave amplitude.

A still further object is to provide a thermal jet engine of the class described wherein the combustion gases may be kept separate from the standing wave fluid column, to the end that the standing wave fluid column may consist of clean air.

One form of the present invention, first disclosed in my aforesaid prior copending application Serial No. 439,926, includes a movable element in the form of a diaphragm separating the combustion region from the closed head end of the fluid column. This diaphragm at once separates the products of combustion from the standing wave column, giving increased acoustical impedance in the column, and confines the explosion gases so as to permit substantially improved compression and expansion ratios. Further, the confinement of the heated combustion gases results in a cold standing wave column, and because the velocity of sound (and hence its wave length) is a function of temperature, there results a substantially shortened standing wave column for any given frequency. Thus a more compact apparatus is achieved. There is also the advantage of providing an inductive coupling mass between the explosion and the fluid column which serves to improve the "Q" of the system, the factor "Q" being understood to denote what may in a general way be thought of as the "fly-wheel effect" of the system.

The invention will be best understood by now referring to certain present illustrative embodi-

ments thereof, reference for this purpose being had to the accompanying drawings, in which:

Figure 1 is a longitudinal sectional view of one illustrative embodiment of the invention;

Figure 2 is a fragmentary view of a modification;

Figure 3 is a view similar to Figure 1 but showing a further modification;

Figures 4, 5 and 6 are longitudinal sections of still further modifications of the invention;

Figure 7 is a side elevation, partly in longitudinal section, showing a present preferred embodiment of the invention;

Figure 8 is a section taken on broken line 8-8 of Figure 7; and

Figure 9 is a detail showing a modification of a portion of the engine of Figures 7 and 8.

In Figure 1 of the drawings, numeral 10 designates generally a resonant housing or cavity, which in this instance includes a cylindrical tubing 11 having a somewhat flared open end 12, through which air is alternately drawn in and then discharged to atmosphere, and having a flange connection 13 at its opposite end with a head 14 forming a somewhat restricted combustion space 15.

Mounted between the rearward or flanged end of tubing 11 and the head 14 is a piston-type flexible diaphragm 16 consisting of a relatively rigid piston portion 16a joined by an elastic compliance 16b to a marginal rim portion which is clamped between the adjacent flanges on the tubing 11 and the head 14, as will be clear from Figure 1.

This diaphragm has a finite mass, and its compliance 16b gives it stiffness, whereby a return stress is developed upon deformation in either direction from its normal median position. Having both mass and stiffness, the diaphragm becomes a vibratory system possessing a resonance frequency, and it is usually tuned to a frequency somewhat higher than the fundamental frequency of the resonant housing 10 because this choice of tuning tends to improve coupling between the two systems. As will later appear, this diaphragm oscillates in step with the frequency of combustion within chamber 15, being driven by that combustion, and operates to transmit the pressure pulses developed in the combustion chamber to the fluid column within tubing 11.

Cooperating with a suitable valve seat formed within head 14 is an intake valve 20 supplied with a combustible mixture through a pipe 21 to which the mixture is fed from a supercharger 22, the mixture being formed by a suitable carburetor 23. Also cooperating with a suitable valve seat formed within the head 14 is an exhaust valve 25 controlling the flow of exhaust gases through a passage 26. The intake and exhaust valves are operated in suitable sequence by cams 27 and 28, respectively, on a cam shaft 29 which drives the supercharger 22 and magneto 30, and which is driven by a cam shaft drive means 31 which may be any speed-governed drive, such as an electric motor, internal combustion engine, turbine, etc. As an alternative or supplementary fuel supply means, there may be provided a fuel injector pump 32 driven from cam 33 on cam shaft 29 and acting to meter a liquid fuel directly into the combustion chamber 15 through a suitable spray type injection nozzle 34. Fuel can be mixed with the air in the carburetor 23 to form a lean mixture delivered to the combustion chamber through intake valve

20, and additional fuel in liquid state can be supplied, preferably during periods of high pressure in the combustion chamber, by use of the injector pump 32. Alternatively, the carburetion system or the injection system may be utilized individually, and if it be desired to inject all of the fuel into the combustion chamber, the necessary air for combustion will be supplied through the intake valve from the supercharger 22. Of course, the magneto 30 and cams 27, 28 and 33 should be arranged to provide the desired sequence of events including introduction of fuel, ignition (as by use of spark plug 35 connected to magneto 30) and exhaust of the combustion products. In this connection, the angular relationship of the means operating the magneto and valves from the shaft 29 can be made adjustable, for instance, by using a standard spark advance mechanism of the type incorporated in conventional magnetoes.

The events of the operating cycle include, in sequence, (1) delivery of the fuel charge to the chamber 15 upon opening of the intake valve and movement of the vibratory diaphragm 16 toward the right, (2) compression of the admitted fuel charge upon return movement of the diaphragm (toward the left), (3) ignition of the fuel charge and consequent creation of a positive pressure pulse which drives the diaphragm back toward the right, causing the pressure pulse to be transmitted to the fluid column, and (4) opening of the exhaust valve and return of the diaphragm to scavenge the combustion chamber. The intake valve 20 preferably opens a short interval of time before the exhaust valve 25 closes, thereby scavenging exhaust gases from the combustion chamber in a manner similar to "valve lap" timing utilized in conventional internal combustion engines. If additional fuel is desired by injection, the pump 32 preferably injects it during either the "intake" or "compression" events.

The speed of the cam shaft 29 is so regulated that the explosions or pulses generated in combustion chamber 15 occur at such timed relationship as will establish a condition of standing wave resonance in the fluid column within the tube 11, the tube behaving substantially as a quarter-wave organ pipe, with a pressure anti-node region P adjacent the closure formed by diaphragm 16, and with a velocity anti-node V at the open end 12. It will, of course, be understood that for a tube 11 of given length, there will be a corresponding explosion frequency necessary to establish the desired resonant operation, and the cam shaft 29 is driven at a speed to achieve such a condition. One method of accomplishing this purpose is to note the peak reading of a pressure gage 36 communicating with the pressure anti-node region P of the apparatus. This gage will obviously show a maximum reading at resonance. The reading on the gage 36 will indicate the magnitude of the thrust, since this thrust results, at least in part, from the action of each wave pulse against the diaphragm 16 in accordance with radiation pressure principles set forth in my aforesaid Patent No. 2,480,626.

It may be noted in connection with the establishment of the pressure anti-node P that the diaphragm 16 should be stiff enough to reflect pressure waves or pulses returning to it from the open mouth 12 of the tube in the general manner of the closed end of a quarter-wave organ pipe. In view of the travel of the dia-

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phragm, a region P of zero to-and-fro oscillation cannot be achieved, but a substantial pressure anti-node P is established. This means, in effect the creation of a zone P which is of high acoustic impedance (large ratio of pressure amplitude to velocity amplitude).

If the diaphragm 16 had negligible mass and stiffness, it would move at all times in such a manner that the pressure cycle at the anti-node P would be in phase with the pressure cycle in the combustion chamber 15. Assuming, however, a finite mass for the piston and a compliance of suitable stiffness, a phase lag is introduced between the pressure events in the combustion chamber and those transmitted to the end of the fluid column. Operation may then be as follows:

The explosion within chamber 15 creates a pressure disturbance producing a positive pressure pulse which moves diaphragm 16 to the right, thereby transmitting the positive pressure pulse to the end of the fluid column within the tube 11 and thence toward the right along the fluid column, the wave traveling with the speed of sound to the open end 12 of the tube, which expands it into the open atmosphere. Normally the diaphragm will be substantially at its extreme position toward the left at the instant of explosion. At a time substantially 90° following the explosion, the diaphragm passes through the mid-position of its forward or power stroke travel toward the right, and at such time transmits peak positive pressure to the end of the fluid column. The diaphragm will thereafter complete its stroke to the right and then move through a return stroke (leftward) by virtue of the energy stored in its stressed compliance.

The positive pressure pulse launched down the tube by the described forward stroke of the diaphragm is reflected from the open end of the tube as a negative pressure pulse (wave of rarefaction), the peak of which arrives at the diaphragm one-half cycle after the positive pressure pulse peak at the diaphragm and just as the diaphragm is at the mid-point of its return stroke (leftward). The diaphragm continues toward the left, and this movement together with the negative pressure pulse already mentioned creates a substantial pressure depression in the region immediately to the right of the diaphragm. The said return stroke of the diaphragm (toward the left) operates to scavenge the combustion chamber, the exhaust valve 25 being open at this time. The described negative pressure pulse is reflected by the diaphragm as a negative pressure pulse moving toward the right, which is reflected from the open end to return a half-cycle later as a positive pressure pulse that arrives at the diaphragm with peak positive pressure as the diaphragm passes with maximum velocity through the mid-position on its next forward stroke (toward the right). A positive pressure peak is thus built up to the right of the diaphragm, while a suction is created within chamber 15 by which fuel is taken in through the then open intake valve 20. A positive pressure pulse is then reflected from the diaphragm, and returns a half-cycle later (after reflection at the open end) as a negative pressure pulse reaching the diaphragm with peak pressure as the latter passes through the mid-position of its compression stroke (leftward). The negative pressure pulse is in turn reflected by the diaphragm and a half-cycle later will return from the open end as a posi-

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tive pressure pulse arriving with peak positive pressure just as the diaphragm passes through its mid-position on the succeeding "power" stroke. A positive pressure peak will thus again be created to the right of the diaphragm as the diaphragm crosses the mid-point of its forward power stroke, and the succeeding cycle proceeds as before. The maximum pressure in the chamber 15 occurs instantly after the explosion, when the diaphragm is in its extreme leftward position. The maximum positive pressure in the region immediately to the right of the diaphragm occurs 90° of the cycle later, with the diaphragm at the half-way point of its return stroke, moving with maximum velocity. The pressure wave at the head end of the fluid column in tubing 11 thus lags by 90° the pressure events in the combustion chamber, the intervening diaphragm functioning as a coupling introducing substantially a 90° phase lag.

Thus, briefly summarizing, as every alternate positive pressure pulse launched down the tube from the combustion space 15 and diaphragm 16 returns as a reflected positive pressure pulse, a new explosion has occurred to build an augmented positive pressure peak and launch a succeeding positive pressure pulse. Intervening positive pressure pulses return to the diaphragm 16 at intervals of one cycle to build intervening positive pressure peaks. The negative pressure pulses arriving at the diaphragm augment the negative pressure "dips" produced by the diaphragm, and thus strengthen the wave. The tube 11 accordingly behaves as a quarter-wave organ pipe, cyclically excited by intermittent combustion generated impulses at a sub-multiple (here one-half) of its resonant frequency. In accordance with quarter-wave pipe theory, a standing wave is established in the tubing, with a pressure anti-node P adjacent the diaphragm 16, and a velocity anti-node V at the open end or tail 12. At the pressure anti-node P, as well as within the combustion zone 15, alternate positive and negative pressure peaks are experienced, and these create a radiation pressure thrust on the diaphragm in accordance with principles explained in my application Serial No. 439,926. At the pressure anti-node zone P, to-and-fro oscillation of the fluid is, of course, minimized. At the velocity anti-node region V, however, the air moves to-and-fro into and out of the open end of the tubing with substantial amplitude. Outside air is alternately drawn into the end of the tube from virtually all directions, and expelled in a rearward axial direction with increased momentum, thereby creating a thrust by jet discharge.

The diaphragm 16 affords a coupling mass between the combustion zone and the fluid column which serves to increase the "Q" of the system, and at the same time provides the further advantage that products of combustion are kept separate from the standing wave fluid column, which results not only in further augmented "Q," as already explained, but also in an unheated fluid column, which hence becomes substantially shorter for a given wave frequency.

The pressure amplitude of the standing wave is proportional to the velocity amplitude of the diaphragm, which latter is largely determined by the product of frequency and stroke. The expansion ratio, or pressure amplitude, in the combustion space can be independently modified by designing the "clearance volume" or proximity of the head 14 to the extreme inward travel (to the

left) of the diaphragm. In this manner combustion pressure range can be many times that of the wave.

The modification represented in Figure 2 consists simply of a substantially quarter-wave tube 40, open at one end 41, and provided at its opposite end with a closure head 42 carrying a cylinder 43 for a reciprocating piston 44, the latter being driven from crank shaft 45 (powered in any suitable manner, as by power source unit indicated at S) through crank 46 and connecting rod 47. It will be understood that unit S drives crank shaft 45 at the proper rotational speed to reciprocate piston 44 at a resonant frequency of tubing 40, so as to establish a velocity anti-node region V at the discharge end of the tubing, and a pressure anti-node region P at the head end of the tubing. The system of Figure 2 is thus fundamentally similar to that of Figure 1, the piston 44 of Figure 2 being substituted for the movable diaphragm 16 of Figure 1, and the connecting rod and crank for the combustion. Operation of the system of Figure 2 is essentially the same as that of Figure 1, excepting for the combustion cycle characteristics of Figure 1. Waves of condensation and rarefaction returning to the closed end of the tubing 40 are reflected partly by the piston 44 and partly by the head 42 surrounding the piston, and radiation pressure effects resulting in the creation of a thrust are experienced on both the piston and the head 42.

The embodiment of Figure 3 is similar in many respects to that of Figure 1, and for convenience corresponding parts will be identified with similar reference numerals but with the suffix *a* added in the case of Figure 3. Thus the cylindrical tubing is indicated by numeral 11a, and this tubing is flange connected at its head end with head 14a forming restricted combustion space 15a. Cooperating with a suitable valve seat formed within head 14a is an intake valve 20a supplied with a combustible mixture through pipe 21a to which the mixture is fed from supercharger 22a, the mixture being formed by carburetor 23a. Also cooperating with a suitable valve seat formed in head 14a is an exhaust valve 25a controlling the flow of exhaust gases through a passage 26a. The intake and exhaust valves are operated in suitable sequence by cams 27a and 28a, respectively, on a cam shaft 29a which drives the supercharger and magneto 30a, and which is driven by a cam shaft drive means 31a which may be any speed-governed drive, such as an electric motor, internal combustion engine, turbine, etc. As an illustrative or supplementary fuel supply means, there may be provided fuel injector pump 32a driven from cam 33a on a cam shaft 29a and acting to meter a liquid fuel directly into combustion 15a through injector nozzle 34a. The operation of the fuel system may be, of course, as previously described in connection with Figure 1. The magneto 30a and cams 27a, 28a and 33a should be arranged to provide the desired sequence of events including introduction of fuel, ignition (as by means of spark plug 35a connected to magneto 30a), and exhaust of the combustion products, all as explained in connection with Figure 1. A pressure gauge 36a is shown as communicating with the head end region of the tubing 11a. The tubing 11a has a closure 50 at its end remote from combustion chamber 15, and fluid is discharged from the tubing via one or more outlet pipes 51 controlled by exhaust valves 52 operated by suitably driven cams 53, each valve 52 being provided with a seat within a valve

chamber 54 which communicates with the interior of tubing 11a in the region of end closure 50. If the apparatus is to be designed for generation of a thrust, the discharge pipe or pipes 51 are oriented to discharge in a rearward axial direction, as indicated. It is to be understood that a number of such exhaust valve devices may be distributed around the end portion of tubing 11a.

An intake pipe 56, or plurality of intake pipes 56, each controlled by an intake valve 57 provided with a seat within a valve chamber 58 and operated by a suitable driven cam 59, may be arranged to introduce air into the tubing 11a, preferably in the region of end closure 50. Cams 53 and 59 are driven through any suitable driving arrangement so as to open the respective valves during alternate half cycles. The exhaust valves are timed to be open when flow within the tubing 11a, in the region of the valves, is toward the right, and the intake valves are timed to be open when said flow is toward the left. The valve controlled intake and discharge openings are of sufficient cross-sectional area to provide a zone of low acoustic impedance near the end wall 50, which is to say that a velocity anti-node V is established at said zone. With substantially or unduly restricted intake and discharge openings, the air flow therethrough as compared to pressure amplitude might be sufficiently small that a high impedance condition would be created, and no velocity anti-node at V would be obtained. Therefore, it is necessary that the cross-sectional areas of the valved passages be adequate, and/or that sufficient of said passages be provided. When this condition is satisfied, the apparatus will behave as though it were open rather than closed at the end 50. The sound wave reaching the end 50 will be "expanded," and a reflection will occur sending a negative pressure wave back up the tubing 11a. To generalize somewhat, it may be seen that what is required at the end of the tubing in any case is a "wave expanding means," and this might be a wide open end (Figure 1), an end provided with a valve controlled discharge of sufficient area, or even a capacitance chamber such as shown in my aforementioned Patent No. 2,480,626. The system of Figure 3 has the advantage that the quantity of air pumped from the intake pipes through the exhaust pipes will be under control. Elevated pressures within the tubing 11a can be used as by increasing the pressure on the intake pipes, giving high mean pressures within the system, with attendant improvement in "Q."

The other difference in the embodiment of Figure 3 as compared with that of Figure 1 is the substitution of a piston 60 for the diaphragm 16. As here shown, this piston 60 has projecting therefrom a piston rod 61 passing through a spider 62 welded or otherwise secured within tubing 11a, a coil compression spring 63 being placed around rod 61 between piston 60 and spider 62, and a similar spring 64 being placed around rod 61 between a head 65 on its rearward extremity and the said spider 62.

The piston of Figure 3 behaves and functions in a manner entirely analogous to the diaphragm 16 of Figure 1, the springs 63 and 64 yielding to cushion and stop the piston at the two ends of its stroke, and the spring energy so stored moving the piston through its return stroke in each direction to provide the oscillatory system. The mass of the piston assembly and the constants of these springs may be so chosen as to give a fundamental oscillation frequency which is

slightly higher than the fundamental resonant frequency of the tubing 11a, causing the piston motion to be better controlled by the wave. By "over-tuning" the moving element, it would like to over-speed but is held back by the sonic load (standing wave); thereby giving good power factor of energy transfer to the sonic load. The apparatus of Figure 3 operates similarly to that of Figure 1, and a detailed description hence need not be given. As already mentioned, the valved tail portion of the apparatus is designed to give a low impedance, velocity anti-node region V, while the reaction of piston oscillation is sufficiently restricted to give a high impedance pressure anti-node region P adjacent the piston. The traveling positive and negative pressure waves set up in tubing 11a will be reflected with "inversion" (e. g., positive to negative pressure) by the velocity anti-node region V, and without inversion by the piston 60, giving substantial quarter-wave characteristics, with a standing wave established in the tubing 11a when the explosion frequency is adjusted to resonate the tubing. The piston 60 experiences a substantial radiation pressure thrust toward the left as a result of the large pressure variations of the standing wave at the anti-node region P, in accordance with radiation pressure principles set forth in my Patent No. 2,480,626, and this thrust is transmitted to the tubing 11a through rod 61 and support 62. Thrust results also from directed mass discharge of air from rearwardly discharging exhaust pipes 51. In this connection, if the apparatus is to be used for jet propulsion, the intake pipes 56 should not be rearwardly directed at their intake points, lest the jet discharge effect be cancelled. Preferably, the intake openings face forwardly, though they may face laterally. If the apparatus is to be used as a pump or compressor, the discharge pipes 51 may lead to a suitable tank or accumulator (not shown).

Figure 4 shows another embodiment, wherein the tubing or conduit 11c is open not only at its far end 12c, but also at its near or "head" end 70. Axially aligned with but spaced from the tubing 11c is a separate cylinder 71 having an open end 72 facing tubing 11c and having a head 73 closing its opposite end. Working within this cylinder 71 is a piston 74, and between the piston and head 73 is the combustion space 75, the head being provided with a spark plug 76. Communicating with an intermediate portion of cylinder 75 is a fuel intake pipe 76, the air being taken in by way of scoop 77 and the mixture being formed by means of carburetor 78. Cylinder 71 is also provided with an exhaust pipe 80, which may discharge to atmosphere, but which is here shown as communicating with the interior of tubing 11c near the head end thereof to provide flow of additional fluid within the tubing 11c.

The head end portion of tubing 11c is cylindrical in shape, and reciprocating therein is a piston 82. The head 83 of this piston is formed with a hub 84 tightly mounted on a piston rod 85 which extends to and is rigidly connected to the aforementioned piston 74. Piston rod 85 passes through a support 86 which is mounted on the frame structure 87 to which the tubing 11c and the cylinder 71 are both rigidly connected, as somewhat diagrammatically indicated in Figure 4. Between this support 86 and the piston 74 is a coil compression spring 88, and between support 86 and a collar 89 loosely mounted on rod 85 is compression spring 90. To provide for still more fluid flow within the tubing 11c, piston head

83 is shown as provided with air intake ports 91 equipped with vibrating reed-type valves 92, tuned preferably to a resonant frequency somewhat higher than the fundamental frequency of the tubing 11c. Motion of piston 82 assists opening and closing of valve member 92 by momentum, and they are also responsive to pressure fluctuations at the pressure anti-node region P. It will later become evident that these two valve operating influences are additive.

The driving piston 74 is in this instance operated in the manner of a conventional two-cycle combustion engine. The piston 74 is cushioned and stopped on each stroke toward the right by means of compression spring 88, and this spring returns the piston toward the left when the force of the explosion is spent. The return stroke of the piston is cushioned by compression of the fuel charge trapped within the head end of the cylinder, and alternately stopped by the explosion in the cylinder. Spring 90 serves as a safety device in case the piston is not so stopped, being compressed upon engagement of hub 84 with collar 89.

The reciprocating piston 74 moves piston 82 back and forth in the head end of tubing 11c with operation generally similar to that already described in connection with Figures 1-3. The piston 74, operating however upon a two-cycle principle, acts through rod 85 and piston 82 upon each forward stroke to transmit a positive pressure pulse from the combustion to the fluid column in tubing 11c. This pulse returns to piston 82 a half-cycle later (after reflection at the open end 12c) as a negative pressure pulse, the piston then being at the mid-position of its return stroke at peak negative pressure. A half-cycle later, this negative pressure has been reflected at the piston, then again at the open end, and the wave is back to the piston as a positive pressure pulse, while the piston has been to its extreme left hand position, and then been driven back by an explosion in the cylinder to the mid-position of its power stroke. Behavior is thus as in Figure 1, with the exception that an explosion occurs each time the piston 74 reaches the top of its cylinder. Analysis will again show that the peak positive and negative pressures at the pressure anti-node region P will occur with the piston moving at maximum velocity at the mid-position of its stroke (lagging the pressure cycle in the cylinder 75 by substantially 90°).

The exhaust flow through pipe 80 into cylinder 11c will occur at approximately mid-stroke, or during the positive pressure peak in tubing 11c, so as to increase said peak. During the middle portion of the return stroke of piston 74, the negative pressure then existing at P results in further flow through pipe 80 to aid in scavenging the cylinder. Also during negative pressure half-cycles at the pressure anti-node region P, the reed valves 92 open automatically to permit additional air to be taken in. The intake of air, both by way of pipe 80 and by way of valves 92, assures sufficient fluid within tubing 11c to provide for relatively high wave energy density even though return flow at the open end may be limited. In this connection, it should be explained that for high velocity jet propulsion, the quantity of air that may be sucked into the open tail of the apparatus decreases as a result of the slipstream effect, with the end result that a limitation is set on the velocity that can be achieved. The provision for additional air through the apparatus satisfies this air starvation.

Figure 5 shows another modification, which is in many respects similar to that of Figure 4, and corresponding parts are accordingly designated by the same reference numerals but with the suffix *d* in the case of Figure 5. The exhaust pipe 80*d* leading from cylinder 7'*d* may in this instance discharge to atmosphere, though the arrangement of Figure 4 may be employed if desired. Also, if desired, an air intake pipe 93, substantially a quarter-wave in length, and having at its air intake end an air scoop 94, may open into tubing 11*d* near the pressure anti-node region P. Such a quarter-wave pipe, opening into a pressure anti-node zone, will feed air into the system, without loss of wave energy from the system, and without the necessity of valves for controlling the pipe. This device is disclosed in my prior Patent No. 2,480,626, and is claimed in my copending application Serial No. 728,766, filed February 15, 1947, entitled Standing Wave Jet Propulsion Apparatus With Valveless Air Intake Conduit. The pistons 74*d* and 82*d* are interconnected by connecting rods 95 and 96 and a crank 97 on a common crank shaft 98, so that the two pistons will reciprocate together. In this case, the springs 88 and 90 of Figure 4 are avoided, the crank throw setting the limits of piston travel, and crank shaft momentum (augmented by a flywheel, if necessary) providing for return travel of the pistons following the power stroke. The radiation pressure thrust on the piston 82*d* will in this instance be transmitted to the frame 87*d* of the apparatus via connecting rod 96, the crank shaft, and the crank shaft bearings (not shown).

It has already been mentioned that under high velocity conditions, such an apparatus as here described may become "starved" for air. Air is drawn into the open tail of the resonant tubing from virtually all directions during every other half-cycle, and is expelled or jetted therefrom in a straight rearward direction during the remaining half-cycles, thus giving a net thrust in a forward direction. But with increasing velocities, the kinetic energy of the slip-stream air flow around and past the apparatus reduces the quantity of air that can be pulled inwardly and reversed in direction so as to enter the open tail, with the result that the air supply to the apparatus pinches down, and a self-imposed limit is thus set on the maximum air craft velocity that can be achieved by the apparatus.

Figure 6 shows a jet propulsion apparatus in accordance with the invention having a form of tail designed to augment the air supply thereto and thus increase the maximum velocity that can be attained, it being understood that such a provision may be employed on any of the forms of jet propulsion apparatus described herein. The specific apparatus of Figure 6 has a cylindrical tubing 108 having a reciprocating piston 109 in the head end thereof, and this piston may be reciprocated by any suitable means at a resonant frequency of the apparatus (preferably the fundamental). Surrounding the tubing 108 toward the discharge end thereof, and annularly spaced therefrom, is a tubing 110 whose rearward end is joined to tubing 108. Within the region covered over by the tubing 110 is a plurality of air intake ports 111, controlled by vibrating reed valves 112, of a well known type. The tubing 110 is designed to catch boundary layer air around the tubing 108 and to direct it to flow inwardly through the ports 111 into the tail portion of tubing 108, thus satisfying the air re-

quirements of the apparatus notwithstanding relatively high forward velocities. Additionally, the apparatus of Figure 6 is shown as provided just beyond air intake ports 111 with an end closure 113, having discharge ports 114 controlled by vibrating reed valves 115. The tail portion 108*a* of the tubing may project somewhat beyond end closure 113 to provide a jet discharge nozzle. The discharge ports 114 are of a total area sufficient to give the effect of an "open end" to the tail of the apparatus, creating a low impedance, velocity anti-node region V thereadjacent. The valves 115 hold a little back pressure on the fluid column in the tubing, increasing the mean pressure level, and thereby the "Q" of the system.

Reference is next directed to the preferred embodiment of the invention shown in Figures 7 and 8. Numerals 120 and 121 show a symmetrical pair of divergent, horn-like resonant housings or cavities providing a pair of generally parallel fluid conduits, the small or neck ends of which communicate with a piston chamber 122 of a two cylinder, free-piston engine designated generally by numeral 123. Engine 123 embodies a pair of opposed, axially aligned engine cylinders 124 and 125. Each of cylinders 124 and 125 joins the chamber 122, which is defined by a cylindrical sidewall 126, and angular endwalls 127, disposed at angles of approximately 60 degrees to the axis of the cylinders, as clearly shown in Figure 7. The smaller end portions of the conduits 120 and 121 are curved somewhat toward one another and joined to the angular walls 127 of chamber 122 at substantially right angles thereto, the walls 127 being ported so that the conduits 120 and 121 communicate freely with the chamber 122. The far or open ends of conduits 120 and 121 discharge in substantially parallel directions, perpendicular to the axis of the engine cylinders 124 and 125. As already mentioned, the conduits 120 and 121 are preferably somewhat divergent, though not as divergent as might appear from Figure 7, there being preferably a moderate convergence in the plane at right angles to Figure 7, as will appear from an inspection of Figure 8. Overall, the conduits 120 and 121 may be considered to have, preferably, a small degree of divergence, though this is not essential to the invention.

The engine 123 is illustratively, though not necessarily, of a two-cycle type, and each of cylinders 124 and 125 is accordingly provided with an appropriate fuel-air intake pipe 130, air being understood to be drawn in through the flared scoop-end 131 thereof, and a fuel mixture being formed by carburetor 132. Each of cylinders 124 and 125 is provided with an exhaust pipe 134 connected in the manner conventional in two-cycle engines. These exhaust pipes 134 are here shown as connected to the convergent end portions of the conduits 120 and 121. In this connection, for a reason which will appear presently, the exhaust from cylinder 124 is introduced to conduit 121, and the exhaust from cylinder 125 is introduced to conduit 120. In a modification, indicated in Figure 9, the exhaust pipes, here designated by numeral 134*e*, discharge to atmosphere.

Working within cylinders 124 and 125 is a unitary free piston structure 140 consisting of a piston 141 working within cylinder 124, a piston 142 working within cylinder 125, and an enlarged "acoustic" piston 143 working within enlarged chamber 122, the piston 143 having angular sides 144 of the same angle as the angular end walls 127 of chamber 122, so that clearance space be-

tween the acoustic piston 143 and the ends of the chamber 122 may be reduced substantially to zero. The heads of the two cylinders are provided with spark plugs 150, and these are energized under the control of the reciprocation of the free piston. As one illustrative expedient, the piston member 143 may be provided with a cam rod 151 projecting oppositely therefrom and outwardly through suitable close-fitting passages in the end walls 127 of chamber 122. Opposite ends of this cam rod are formed with cam surfaces 152 engageable with breaker arms 153. Each of spark plugs 150 is connected to the high voltage terminal of a conventional induction coil 154, the low voltage circuit of which includes a battery 155 and a make-and-break switch 156 controlled by breaker arm 153. Thus, at the end of each stroke of the free-piston structure, cam rod 151 operates a breaker arm 155 to open the switch at 156 and break the low voltage circuit, thus causing a spark to occur at plug 150 in the conventional manner.

In designing the engine, a piston mass is chosen which will not produce a stroke giving excessive combustion pressures at the intended frequency of operation. A typical engine for a 50 cycle/sec. engine, having a cylinder 124 of 2" bore, has a piston of the order of two pounds, giving a stroke of about 6". The thermal expansion ratio is controlled by adjusting the combustion chamber clearance volume at top dead center relative to piston stroke, and can be increased merely by increasing the mass of the free-piston. In other words, higher gas pressures are required to stop the heavier piston at each end of its stroke.

Upon the occurrence of an explosion, say in cylinder 123, the free-piston is driven downwardly, and the acoustic piston head 143 creates a positive pressure pulse which is introduced into horn 121 and traverses the latter to its open end. The explosion frequency of the engine is easily adjusted to the fundamental resonant frequency of the horns 120 and 121, which behave substantially as quarter-wave cavities, with high impedance pressure anti-node regions P at their ends coupled to the free-piston, and with low impedance velocity anti-node regions V at their open ends. Accordingly, the positive pressure pulse launched, for example, down the horn 121 is reflected from the open end thereof as a negative pressure pulse, which arrives with peak negative pressure at the beginning or smaller end of the horn and at the space in cylinder 122 between the horn and piston portion 143 as the latter is mid-way on its upward return stroke. A reflection of this negative pulse occurs, and a negative pulse travels down the horn, to be reflected from the open end as a positive pulse which will pass through the small end of the horn and arrive at piston portion 143 with peak pressure at the midpoint of the down stroke. The engine operating on a two cycle principle, the cycle is in general like that described in connection with Figure 4. It should be noted, however, that the engine in this instance is of a twin, opposed type, with explosions occurring in the two cylinder heads at opposite ends of the stroke of the free piston. Both sides of the acoustic piston are thus used for wave generation, the lower cooperating with lower horn 121, and the upper with upper horn 120. A polyphase effect is thereby achieved at the discharge ends of the two horns, with resulting reduction of objectionable noise. It should be evident that the exhaust pipes 134 when

connected into the horns in the manner of Figure 7 are precisely analogous to the pipe 80 of Figure 4, functioning as in the apparatus of Figure 4 to supply fluid to the resonant conduits.

Analyzed acoustically, the apparatus of Figures 7 and 8 has regions equivalent to high acoustic impedance in the combustion chambers of cylinders 123 and 124, regions of low acoustic impedance at the discharge ends of "horns" 120 and 121, and regions of intermediate acoustic impedance at and adjacent the junctures of the small ends of the horns with the cylinder 122. The high impedance point of each horn is of course at P, the pressure anti-node region, where pressure is relatively high and velocity relatively low. The horn as a unit, however, is a device of relatively low impedance as compared with a generator constituted by a combustion driven piston such as 141 and 142, the problem of a high impedance generator looking into a low impedance load is thus encountered. This problem has been met by the provision of the enlarged acoustic piston portion 143, which will displace an increased volume of fluid at reduced impedance, and thereby adjust the impedance of the generator to that of the horn. It should be evident that between each combustion chamber and the discharge end of the horn which it drives there are in effect two acoustic impedance adjusting transformers in series: first, the free-piston with its enlarged head 143, and second, the substantially quarter wave length horn. These acoustic transformers provide the necessary impedance match between the desirably high impedance combustion and the low impedance load constituted by the atmosphere into which the horns discharge. The free piston may be regarded as the inductive reactance of a tuned acoustic transformer which introduces the proper impedance adjustment between the high impedance combustion and the lower impedance sonic path through the horn.

The embodiment of Figures 7 and 8, probably largely because of the two impedance adjusting transformers in series between the combustion and the jet discharge to atmosphere, develops very great power. Because of this fact it may even be used to achieve vertical flight.

The various embodiments of the invention now disclosed accomplish the various objectives preliminarily outlined. Engines in accordance with the invention have exceedingly high compression and expansion ratio for this class of apparatus, with resultant high fuel efficiency. These embodiments which do not pass heated products of combustion down the resonant tubing have several advantages that follow from cold operation. First, the apparatus becomes shorter because of the lower velocity of sound in the unheated fluid. Second, higher "Q" results from operation on clean air. And third, an apparatus which does not run red hot can more easily be buried in an aircraft structure such as a wing.

It will, of course, be understood that the embodiments here disclosed are merely exemplary of the invention, and that various changes in design, structure and arrangement may be made without departing from the spirit and scope of the invention.

I claim:

1. An apparatus of the character described which includes: a housing defining and containing a column of fluid adapted to have a standing wave established therein, pressure wave reflecting means at one end of said column including a

movable wave-reflecting member, pressure wave expanding means embodied in said housing terminating the other end of said column, pressure disturbance means in pressure transmitting relationship with said fluid column through said movable member and operative to reciprocate said movable member, said reflecting means establishing a pressure anti-node of said standing wave adjacent said one end of said fluid column, and said wave expanding means establishing a velocity anti-node of said standing wave substantially nearer to said other end of said column than to said one end, and inflow and outflow fluid passage means in said housing directing a net flow of fluid which is propelled by said standing wave.

2. A jet propulsion apparatus of the character described which includes: a housing defining and containing a column of fluid adapted to have a standing wave established therein, pressure wave reflecting means at one end of said column including a movable wave-reflecting member, said housing having an opening to atmosphere at the end remote from said wave-reflecting member, said opening locating a velocity anti-node of said standing wave thereadjacent, and pressure disturbance means in pressure transmitting relationship with said fluid column through said movable member and operative to reciprocate said movable member at a resonant frequency of said fluid column to establish said standing wave therein, with a pressure anti-node thereof adjacent said movable member and a velocity anti-node adjacent said opening to atmosphere.

3. A combination as defined in claim 2, wherein said movable member embodies a pressure-transmitting diaphragm across said one end of said column.

4. A combination as defined in claim 2, wherein said movable member embodies a piston slidable in said housing at said one end of said housing.

5. A combination as defined in claim 2, wherein said movable member embodies a piston slidable in said housing at said one end of said housing, in combination with return spring means adapted to cooperate in returning the piston following each forward stroke of the piston.

6. A jet propulsion apparatus of the character described which includes: a housing including walls defining and containing a column of fluid adapted to have a standing wave established therein, pressure wave reflecting means at one end of said column including a movable wave-reflecting member, said housing having an opening to atmosphere at the end remote from said wave-reflecting member for the purpose of alternate fluid intake and jet discharge, said opening also being adapted to locate a velocity anti-node of said standing wave thereadjacent, a combustion chamber in pressure transmitting relationship with said fluid column through said movable member, and means for admitting a charge of fuel and air to said combustion chamber and igniting it at a frequency to excite said fluid column to resonance, thereby to create pressure pulses of resonant frequency reciprocating said movable member and thereby transmitted to said fluid column to establish a standing wave therein, with a pressure anti-node adjacent said movable member and a velocity anti-node adjacent said opening to atmosphere.

7. A jet propulsion apparatus of the character described which includes: a housing including walls defining and containing a column of fluid adapted to have a standing wave established

therein, a reciprocating piston, said housing including walls slidably supporting said piston with one end thereof in communication with one end of said column, said housing having an opening to atmosphere at the other end of said column for alternate intake and jet discharge of fluid, and for the location of a velocity anti-node of said standing wave thereadjacent, said housing also including walls forming a combustion chamber in communication with the other end of said piston, and means for admitting a charge of fuel and air to said combustion chamber and igniting it at a frequency to excite said fluid column to resonance, thereby to create pressure pulses of resonant frequency reciprocating said piston and thereby transmitted to said fluid column to establish a standing wave therein, with a pressure anti-node adjacent said piston and a velocity anti-node adjacent said opening to atmosphere.

8. A jet propulsion apparatus of the character described which includes: a housing including walls defining and containing a column of fluid adapted to have a standing wave established therein, a reciprocating piston having an enlarged head, said housing including a combustion cylinder for said piston and an enlarged cylinder for said piston head, the end of said enlarged cylinder remote from the first named cylinder opening within the housing to one end of said fluid column, said housing having an opening to atmosphere at the opposite end of said column for alternate intake and jet discharge of fluid and means for admitting a charge of fuel and air to said combustion cylinder and igniting it at a resonant frequency of said fluid column, whereby to create pressure pulses of resonant frequency reciprocating said piston and thereby transmitted to said fluid column to establish a standing wave therein, with a pressure anti-node in the region of the juncture of said fluid column with said enlarged cylinder.

9. A combination as defined in claim 8, including also a gas conduit conveying scavenged products of combustion from said combustion cylinder to said fluid column in the region of said one end of said column.

10. A combination as defined in claim 7, including also a gas conduit conveying scavenged products of combustion from said combustion chamber to said fluid column in the region of said one end of said column.

11. A jet propulsion apparatus of the character described which includes: a housing including walls defining and containing a pair of substantially parallel fluid columns adapted to have standing waves established therein, a pair of oppositely extending reciprocating pistons joined by an intermediate piston head of enlarged diameter, said housing including coaxial oppositely extending combustion cylinders for said pistons and an enlarged intermediate cylinder for said intermediate piston head, said housing providing a fluid communication junction between each end of said enlarged cylinder and one end portion of one of the fluid columns, said housing also having openings to atmosphere at the other ends of said fluid column for alternate intake and jet discharge of fluid, and means for admitting charges of fuel and air to each of said combustion cylinders and igniting them alternately at fluid column resonant frequency whereby to create pressure pulses of resonant frequency acting on and reciprocating said pistons in reverse directions, said pressure pulses being transmitted by said piston head to the two fluid col-

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umns to establish standing waves therein, with pressure anti-nodes in the regions of the junctures of said columns with said enlarged cylinder.

12. The subject matter of claim 11, wherein the axis of said cylinders is at right angles to said fluid columns.

13. A jet propulsion apparatus of the character described which includes: a housing including walls defining and containing a column of fluid adapted to have a standing wave established therein, pressure wave reflecting means at one end of said column including a movable wave-reflecting member, said housing having a closure at the end remote from said wave reflecting member, valved air intake and air discharge means communicating with said closed end of said housing, a combustion chamber in pressure transmitting relationship with said fluid column through said movable member, and means for admitting a charge of fuel and air to said combustion chamber and igniting it at a resonant frequency of said fluid column, whereby to create pressure pulses of resonant frequency reciprocating said movable member and thereby transmitted to said fluid column to establish a standing wave therein, with a pressure anti-node adjacent said movable member valve operating means for maintaining said valved intake means open during motion of said movable member toward said one end of said column, and for maintaining said valved air discharge means open during motion of said movable member away from said one end of said column, said air discharge means operating to establish a velocity anti-node of said standing wave within said closed end of said housing.

14. In an apparatus for producing a propulsive thrust by use of sonic principles, the combination of: a sonic column means including a tube containing a fluid column and having reflecting means at one end and a wave expanding means at the other, whereby it will resonate with a pressure anti-node of a standing wave adjacent said one end and a velocity anti-node of said standing wave adjacent said expanding means; means for resonating said column of fluid, including walls defining a combustion chamber in pressure transferring relationship with said one end of said fluid column, a movable pressure responsive element separating said combustion chamber from said fluid column and adapted to transfer pressure pulses therebetween; means for admitting a charge comprising fuel and air to said combustion chamber and igniting said charge at a frequency to resonate said tube; and said tube having fluid inflow and outflow passage means directing a net flow of fluid which is propelled in response to pressure variations of said standing wave.

15. An apparatus of the character described which includes: a housing defining and containing a column of fluid adapted to have a standing wave established therein, pressure wave reflecting means at one end of said column, said reflecting means embodying a movable member mounted in said housing adjacent said one end of said column, pressure wave expanding means embodied in said housing terminating the other end of said column, pressure disturbance means in pressure transmitting relationship with said fluid column operative at a resonant frequency of said fluid column to establish a resonant standing wave therein, said reflecting means establishing a pressure anti-node of said standing

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wave adjacent said one end of said fluid column, and said wave expanding means establishing a velocity anti-node of said standing wave substantially nearer to said other end of said column than to said one end, and inflow and outflow fluid passage means in said housing directing a net flow of fluid which is propelled in response to pressure variations of said standing wave.

16. An apparatus of the character described which includes: a housing defining and containing a column of fluid adapted to have a standing wave established therein, pressure wave reflecting means at one end of said column, pressure wave expanding means embodied in said housing terminating the other end of said column, pressure disturbance means in pressure transmitting relationship with said fluid column operative at a resonant frequency of said fluid column to establish a resonant standing wave therein, said pressure disturbance means embodying a movable fluid displacement member in pressure wave communication with said column, said reflecting means establishing a pressure anti-node of said standing wave adjacent said one end of said fluid column, and said wave expanding means establishing a velocity anti-node of said standing wave substantially nearer to said other end of said column than to said one end, and inflow and outflow fluid passage means in said housing directing a net flow of fluid which is propelled in response to pressure variations of said standing wave.

17. An apparatus of the character described which includes: a housing defining and containing a column of fluid adapted to have a standing wave established therein, pressure wave reflecting means at one end of said column, pressure wave expanding means embodied in said housing terminating the other end of said column, pressure disturbance means in pressure transmitting relationship with said fluid column operative at a resonant frequency of said fluid column to establish a resonant standing wave therein, said pressure disturbance means embodying a movable fluid displacement member in pressure wave communication with said column, and means for applying combustion generated pressure pulses to said member to move the latter, said reflecting means establishing a pressure anti-node of said standing wave adjacent said one end of said fluid column, and said wave expanding means establishing a velocity anti-node of said standing wave substantially nearer to said other end of said column than to said one end, and inflow and outflow fluid passage means in said housing directing a net flow of fluid which is propelled in response to pressure variations of said standing wave.

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