SONIC BURNER HEAT ENGINE WITH ACOUSTIC REFLECTOR
FOR AUGMENTATION OF THE SECOND HARMONIC

Filed Nov. 14, 1955 2 Sheets-Sheet 1

Fig. 1

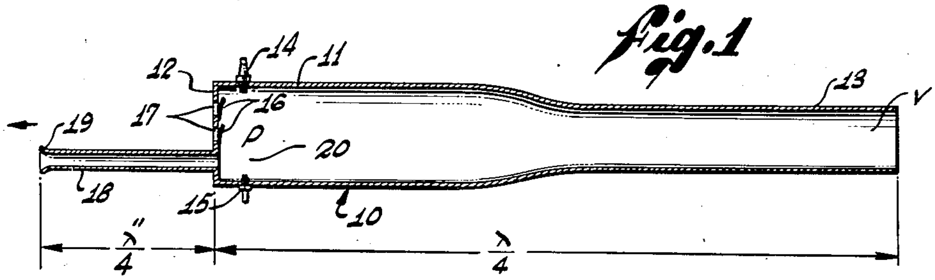

Fig. 2

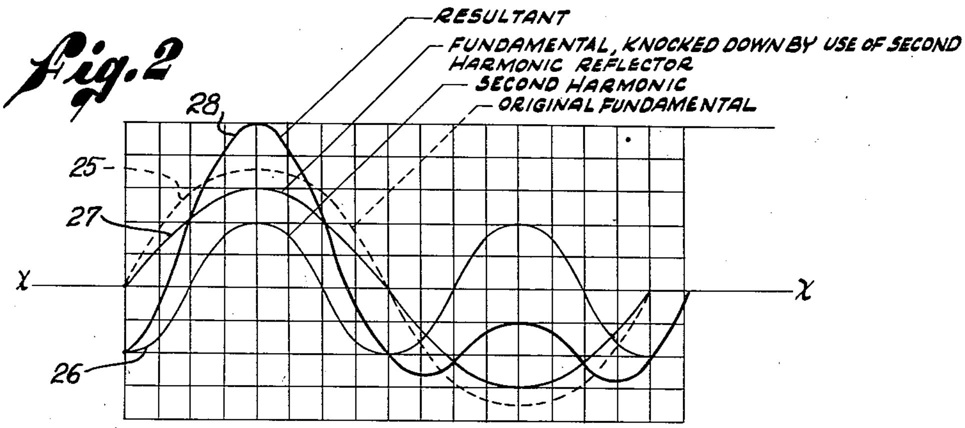

Fig. 3

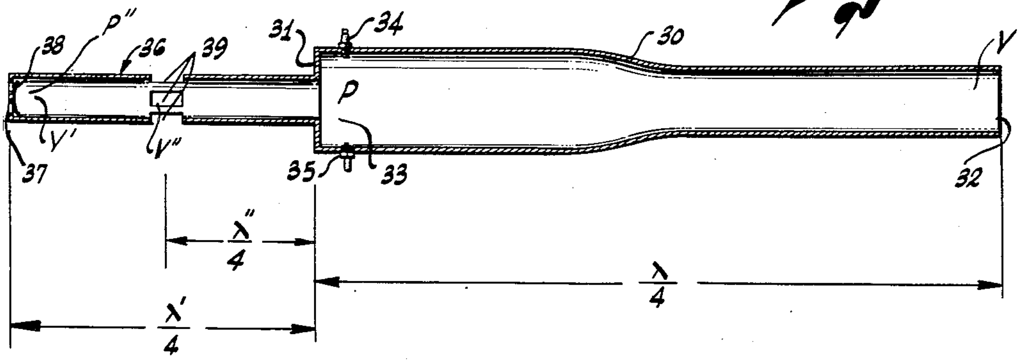

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Fig. 4

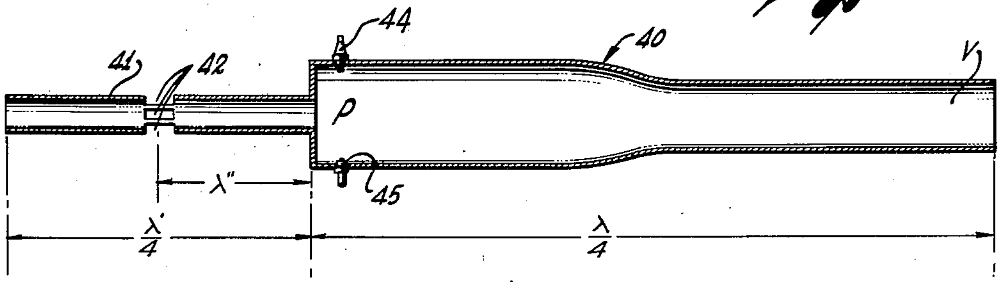


Fig. 5

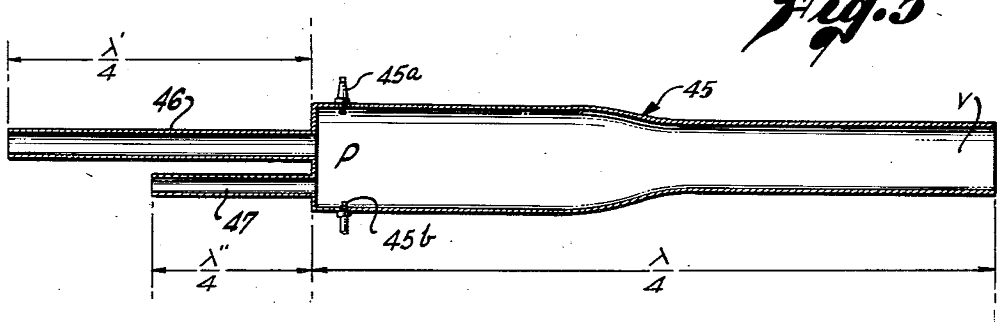
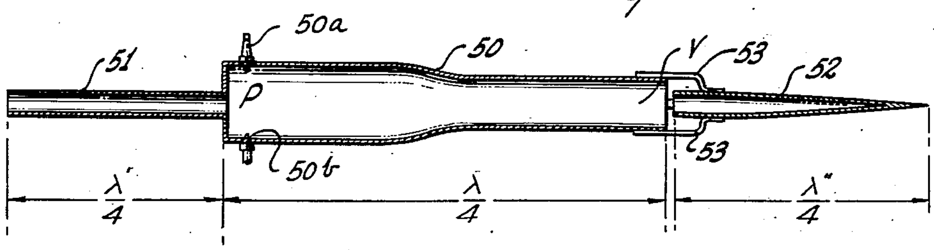


Fig. 6



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SONIC BURNER HEAT ENGINE WITH ACOUSTIC REFLECTOR FOR AUGMENTATION OF THE SECOND HARMONIC

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Application November 14, 1955, Serial No. 546,456

12 Claims. (Cl. 60—39.77)

This invention relates generally to sonic burners as employed in acoustically resonant pulse jet heat engines, i. e., those in which the events of the operating cycle are controlled by acoustic resonance phenomena, and more particularly to means for producing asymmetric acoustic wave shapes in such engines characterized by augmented positive pressure peaks in the combustion chamber for improvement of combustion, expansion ratio, and thermal efficiency, and diminished negative pressure half cycles for aid in retaining the flame throughout the cycle.

For a general discussion of the acoustic theory of engines of the general type to which the present invention appertains, including a discussion of an acoustic valveless air intake pipe, reference is made to my copending application entitled Acoustic Pulse Jet Engine With Acoustic Air Intake System, filed September 1, 1955, Serial No. 532,017, now Patent No. 2,731,795 dated January 24, 1956.

The characteristic feature of sonic heat engines of the type to which the invention relates is a resonant acoustic cavity through which a fluid stream passes, and in which is a combustion chamber region wherein fuel is periodically burned at a resonant frequency of the cavity to establish and maintain an acoustic standing wave having spaced regions within which occur periodic gas pressure and flow velocity oscillations at the resonant frequency. The resonant acoustic cavity possesses at least one region wherein the gas pressure oscillations are maximized and flow velocity oscillations are minimized, known as a pressure anti-node region, and another region at which these conditions are reversed, known as a velocity anti-node region. The combustion chamber is located at the first of these regions, since energy for excitation of the standing wave can best be extracted from the combustion flame at a pressure anti-node. The acoustic cavity may take various physical forms, but for illustration will be assumed to be in the form of a pipe, effectively closed at its head end and open for gas discharge at the tail, in which pipe a quarter wavelength acoustic standing wave may be established in accordance with fundamental organ pipe theory. A pressure anti-node occurs in the closed head end region of this pipe, usually called the burner pipe, and the combustion chamber is located in coincidence therewith. A velocity anti-node occurs at the open or tail end of the pipe.

In such an engine, the resonant acoustic standing wave controls and times the combustion cycle. On each positive pressure swing of the acoustic pressure wave in the combustion chamber, the fuel charge is compressed and ignited. For starting, electric ignition is usually employed; but in normal running, the positive pressure wave sufficiently compresses the fuel charge that combustion occurs by reason of a flame that lingers in the combustion chamber between successive positive pressure swings.

Between such positive pressure swings, an additional fuel charge is accumulated in the combustion chamber. Air is introduced into the combustion chamber either intermittently through valves which open automatically under control of the negative pressure half cycles, or continuously through a valveless air intake pipe such as disclosed in my aforementioned applications. Combustion gases are discharged from the open end of the burner pipe to generate a propulsive thrust.

The effectiveness of combustion and the effective expansion ratio and thermal efficiency of such an engine are governed by the peak value of the positive pressure half cycles in the combustion chamber, so that it is an important advantage to attain high positive pressure peaks in the combustion chamber. Also, the retention of the flame in the combustion chamber during the negative half cycles is somewhat of a problem at high altitudes, as the fire will occasionally blow out under such conditions. It is accordingly undesirable that the negative pressure swings be of large amplitude or attain high peak values.

A general object of the invention may now be stated to be to provide improved means for augmenting the amplitude of the positive pressure peaks in the combustion chamber of an engine of the class described; while a second object is to provide means for simultaneously diminishing the amplitude of the negative pressure peaks.

Best understanding of the acoustic aspects of an engine of the class here involved, and of the functioning of acoustic valveless air intake pipes, is had by resort to the concepts of acoustic impedance. The "characteristic" acoustic impedance at a point in a sound field is defined as the ratio of sound wave pressure p to oscillating gas particle velocity v, and the characteristic acoustic impedance is evidently high at a pressure anti-node, and low at a velocity anti-node. It follows that the combustion chamber of the engine is a region of high acoustic impedance. Moreover, the higher the positive pressure peak in the combustion region, the higher is the acoustic impedance in this region. Since some of the preferred forms of the present invention employ valveless air intake pipes, it is necessary to understand the conditions under which such pipes may be employed. As set forth in my aforementioned Patent No. 2,731,795, the related concept of "analogous" acoustic impedance, commonly referred to as simply "acoustic impedance," and differing from the earlier defined "characteristic" acoustic impedance by appearance of the cross sectional area S of the burner pipe at the combustion chamber in the denominator, is useful in defining broadly the essential acoustic properties of such valveless air intake pipes. Thus, the analogous acoustic impedance is the ratio of sound wave pressure p to the product of v (oscillating gas particle velocity amplitude) and S. Now, if the acoustic impedance of the air intake pipe is designed to be as high as the acoustic impedance within the combustion chamber, at the point of juncture of the air intake pipe therewith, for any frequency component of interest, the air intake pipe will introduce air into the combustion chamber without dissipation of the desired acoustic wave system. As set forth in my aforementioned Patent No. 2,731,795, a quater-wavelength air intake pipe connected to the closed end of a quarter wavelength burner pipe is one specific case that meets this requirement.

The present invention is based upon the concept of engendering, along with the fundamental quarter wavelength standing wave occurring in the system, a double frequency wave component, or second harmonic, so combined with the fundamental as to provide a resultant having an augmented positive pressure peak and a diminished negative pressure peak within the combustion chamber region of the system. The invention provides several means by which this end may be accomplished, one of the simplest of which comprises a valveless air intake pipe which is, in an illustrative example, one-quarter wavelength for the second harmonic frequency. Defined somewhat more broadly, in terms of acoustic impedance, this intake pipe for engendering a second harmonic in the burner pipe has an acoustic impedance which is as high as the acoustic impedance magnitude found by taking the ratio of the desired second harmonic pressure wave amplitude to gas particle velocity at the point of juncture between the air intake pipe and the combustion chamber. The consequence of this provision is that the amplitude of the fundamental frequency pressure wave in the burner pipe is diminished slightly by reason of the presence of the air intake pipe added for augmenting the second harmonic; but the presence of the augmented second harmonic yields a resultant wave having a positive pressure peak materially higher than the amplitude of the positive pressure peak of the original fundamental. And as an added gain, the pressure of the second harmonic gives a negative pressure swing of diminished amplitude as compared with the original fundamental.

The invention may be carried out in a number of variant forms of apparatus, a few representative examples of which will now be described, and for this purpose reference is made to the accompanying drawings, in which:

Fig. 1 is a longitudinal sectional view showing one engine in accordance with the invention;

Fig. 2 is a plot of certain pressure waves against time; and

Figs. 3–6 are views similar to Fig. 1 showing modified forms of the invention.

Referring first to Fig. 1, numeral **10** designates generally a burner pipe such as is now conventional in pulse jet engines, having a forward end portion **11**, closed by forward or head wall **12**, and a tapered section leading to reduced tail pipe **13** open at its rearward end for discharge of combustion gases. The head end region of this burner pipe **10** is equipped, as usual, with spark plug **14** for initiation of combustion, and with suitable fuel feeding means, here indicated as a fuel injector **15**. Head end wall **12** is in this case shown to be provided with a plurality of conventional tuned reed-type valve elements **16** controlling air intake ports **17**, the valve elements being turned to a resonant frequency at least as high as the fundamental frequency of the pipe **10** considered as a quarter wave organ pipe. In addition, a valveless air intake pipe **18** is connected through head **12** into the head end region of pipe **10**, this valveless air intake pipe **18** being here shown to have, at its forward end, an air scoop **19** to facilitate introduction of ram air while the apparatus is in forward motion through the air, in the direction of the arrow in the figure.

The apparatus is of the acoustically tuned, resonant type, in which an acoustic quarter wavelength ($\lambda/4$) standing wave, characterized by a pressure anti-node P in the head end or combustion chamber region **20** of the pipe **10**, and a velocity anti-node V at the open end or tail. Aside from the particular air intake pipe **18**, engines of the type illustrated in Fig. 1 and described in the foregoing are now well known and their operation need be only briefly described herein. Suffice it to say that fuel charges consisting of air admitted past reed valves **16** and fuel introduced at **15** are periodically burned within the combustion chamber region **20**, at the frequency of the fundamental sound wave which is excited within the quarter wavelength pipe **10**. Within the combustion chamber region **20**, a pressure wave is established consisting of alternating positive and negative half cycles relative to some mean value of static pressure. On each positive pressure swing, fuel charge accumulated within the region **20** is compressed and burned, thus driving the positive pressure higher. On each negative pressure swing, the reed valves **16** are caused to open, admitting air for mixture with the fuel introduced at **15** to provide the succeeding fuel charge. The reed valves **16** of course close on the positive pressure half cycles, as is well understood. The apparatus as so far described, and the operation thereof, are now known.

As broadly stated hereinabove, the objective of the present invention, and, in the case of Fig. 1, the purpose of the air intake pipe **18**, is to engender or augment a second harmonic (double frequency) acoustic wave component in the burner pipe **10**. Such a second harmonic wave component will have a pressure anti-node (region of high acoustic impedance) in coincidence with the pressure anti-node N of the fundamental wave. It may be engendered or augmented by a properly applied acoustic impedance, for example, by means of an air intake pipe which presents an impedance which is high for the impedance of the desired second harmonic wave at the pressure anti-node region. An air intake pipe, such as **18**, of one-quarter wavelength ($\lambda''/4$) for this harmonic, satisfies the acoustic impedance requirement. It must be understood that the length of the pipe **18**, if thus designed so that it is one-quarter wavelength for the second harmonic, will be considerably shorter than one-half the length of quarter-wavelength pipe **10**, for the reason that the gases are heated in the pipe **10**, greatly increasing a wavelength distance. Accordingly, when I speak of the pipe **18** as being one-quarter wavelength for the second harmonic, and the pipe **10** as one-quarter wavelength for the fundamental, it will be understood that the temperatures of the fluids in each have been taken into account. It must also be understood that while a pipe **18** of quarter wavelength for the second harmonic satisfies the invention, certain departures from that length are permissible and probably even advantageous under certain conditions; and that, broadly stated, the requirement is that the pipe **18** present an acoustic impedance which is as high as the acoustic impedance within the combustion chamber for the desired second harmonic wave.

The pipe **18** may also be basically considered as an acoustic reflector for the second harmonic, the presence of which assures a substantial second harmonic content. In another manner of speaking, it presents an impedance to a high impedance region of the second harmonic wave component which is conducive to the promotion of that second harmonic.

Fig. 2 is a diagram representative of the pressure waves involved in the phenomena of the invention. At **25** is a graph of the original fundamental pressure wave at the pressure anti-node region P, plotted against time. This wave plot will be seen to be substantially sinusoidal in form, with alternating positive and negative half cycles above and below some value of mean static pressure. Actually, the fundamental is slightly distorted owing to a tendency toward more steeply rising pressure as the fuel charges are ignited. At **26** is the double frequency second harmonic; and it will be noted that its positive pressure half cycle is in phase with the positive pressure half cycle of the fundamental. This second harmonic is attained at the expense of a fraction of the energy of the fundamental, and the fundamental component tends to drop to the wave indicated at **27** as the second harmonic is established. The wave **28** is the resultant of the fundamental component **27** and the second harmonic **26**. Consideration of the several waves will reveal that the positive pressure peak of the resultant wave **28** is materially heightened as compared with the original fundamental, which is the achievement of primary importance. This heightened positive pressure peak results in better combustion, greater transference of energy from the flame to the acoustic wave, greater expansion ratio, and increased thermal efficiency. Also, it will be seen that the negative pressure swing of the resultant wave **28** is decreased or flattened, giving several benefits, one of which is a lessened tendency for the flame to extinguish in the negative pressure interval, which may otherwise occur under certain conditions, such as when the mean static pressure is low, as in high altitude flight.

Fig. 3 shows another embodiment, using a quarter wavelength ($\lambda/4$) burner pipe **30** having head end wall **31** and tail orifice 32, the head end portion of the pipe forming a combustion chamber 33, which is equipped with spark plug 34 and fuel injector 35. It will be understood that the operation of the apparatus will be characterized by the excitation of a fundamental, quarter wavelength sonic standing wave in the pipe 30, with a pressure anti-node at P, and a velocity anti-node at V.

An air intake pipe 36 is connected through head wall 31 into combustion chamber 33. This air intake pipe may have one quarter wavelength for the fundamental wave frequency in pipe 10, as indicated by the symbol $\lambda'/4$, the difference in temperatures of the gases in the two pipes being taken into account. The forward end wall of pipe 36 is formed with orifices 37 controlled by reed valves 38.

It will be seen that these reed valves will be located at a velocity anti-node region V′ of a quarter wavelength standing wave which will be set up in the pipe 36 in sympathy with the quarter wavelength standing wave PV set up in the burner pipe 30. The air intake pipe 36 is additionally formed, midway of its length, with a plurality of open air intake ports 39; and if pipe 36 has a length equal to one-quarter wavelength, the distance from the ports 39 to the junction with the combustion chamber of the burner pipe 30 is then one-quarter wavelength ($\lambda''/4$) for the second harmonic. The open ports 39, at one-quarter wavelength spacing (of the second harmonic) from the pressure anti-node region P, engender a second harmonic wave component in the system, generally as described in connection with Fig. 1, and having the characteristics and consequences diagrammed in Fig. 2 and explained hereinabove in connection therewith. It will be seen that the air intake orifices 39 mark the location of a velocity anti-node region V″ for the second harmonic wave component in the system. Air to form a combustible mixture is taken in via the open orifices 39 at the region V″ as well as past the reed valves 38 at the region V′. It will be seen that the velocity anti-node region V′ for the fundamental wave is also a pressure anti-node region P″ for the second harmonic; and the reed valves 38 open and close in response to the combined influence of the pressure and velocity oscillations to which they are subjected. It is to be noted that the engine of Fig. 3 resembles the engine apparatus disclosed in my aforementioned patent No. 2,731,795.

In Fig. 4 is shown an embodiment similar in general respects to that of Fig. 3, the only exception being the elimination of the reed valves at the forward end of the air intake pipe and their replacement by a valveless orifice. Thus, quarter wavelength ($\lambda/4$) sonic burner pipe 40, in which is excited a quarter wavelength standing wave characterized by pressure anti-node P and velocity anti-node V, and which has spark plug 44 and fuel injector 45, is equipped with valveless air intake pipe 41 connected into the head end wall of the pipe 40. In terms of wavelength, the pipe 41 may, as one example, have a length equal to one-quarter wavelength $\lambda'/4$ of the fundamental, the differences in temperature of the gases in the pipes 40 and 41 taken into account. At the midpoint of the pipe 41 are air intake orifices 42 spaced one-quarter wavelength $\lambda''/4$ of the second harmonic from the juncture of pipe 41 with the pipe 40, as will be understood. More broadly stated from the standpoint of acoustic impedance, the pipe 41 is designed to have an acoustic impedance which is as high as that for the fundamental wave component within the pipe 41; while the pipe 41 from the orifices 42 to the juncture with the pipe 40 has an acoustic impedance which is as high as that of the desired second harmonic wave component at the point of the juncture. The orifices 42 afford a reflection means for the second harmonic, causing the air intake pipe to present to the combustion chamber region, at P, an impedance which is high for the second harmonic and which accordingly encourages or augments the second harmonic component.

Fig. 5 shows another and generaly similar embodiment, having quarter wave ($\lambda/4$) sonic pipe 45, having spark plug 45*a* and fuel injector 45*b*, and equipped with one air intake pipe 46 of high acoustic impedance for the fundamental component of the wave in pipe 45 and another air intake pipe 47 having a high acoustic impedance for the second harmonic wave component of the system. In terms of wavelength, the pipe 46 may be of quarter wavelength ($\lambda'/4$) of the fundamental, and the pipe 47 of one-quarter wavelength ($\lambda''/4$) of the second harmonic (both in relation, of course, to the fundamental resonant frequency wave set up within the pipe 45).

Fig. 6 shows still another embodiment, comprising a quarter wavelength ($\lambda/4$) burner pipe 50, having spark plug 50*a* and fuel injector 50*b*, and having valveless ($\lambda'/4$) high impedance air intake pipe 51, i. e., high impedance for the fundamental wave component, and in this case, a second harmonic wave component is engendered or augmented by use of a reflector 52 mounted on the tail of the burner pipe, of length equivalent to one-quarter wavelength ($\lambda''/4$) of the second harmonic. This reflector 52, which in the illustrative embodiment comprises a tube open at one end and closed at the other, in the present instance tapering toward its closed end, is mounted with its open end opposite the open end of the burner pipe 50, any suitable mounting device as suggested at 53 being employed. It will be seen that the orifice of the pipe 52 is smaller than that of the pipe 50, so that the pipe 50 discharges combustion gases around the outside of the pipe 52. The open end of the pipe 52, however, is positioned to be coupled to the low impedance velocity anti-node region V of the acoustic standing wave system PV of the pipe 50. The pipe 52, thus acoustically coupled to the velocity anti-node region V, and having a length equivalent to half the length of pipe 50, functions as a double frequency reflector. That is to say, it generates a second harmonic wave component in response to the velocity fluctuations of fundamental frequency at the coupling region V. It will be seen that in this case, a reflector capable of engendering a second harmonic has been coupled to a low impedance region of the fundamental standing wave. In other words, the reflector 52 is in this case a low impedance device, coupled to a low impedance region of the fundamental standing wave of the system, but capable of generating a double frequency or second harmonic component, with results equivalent to those described in connection with the foregoing figures.

It will be seen that in all cases, means have been provided for generating or augmenting a second harmonic wave component within the sonic burner pipe, and that this second harmonic, combined with the fundamental wave, produces an asymmetric resultant such as shown in Fig. 2, with heightened positive pressure peaks, and lower or flattened negative pressure swings. This characteristic asymmetric resultant wave shape has been discovered to be of great benefit in the operation of resonant acoustic pulse jet engines, improving combustion, increasing the conversion of heat energy to sonic wave energy, and improving the expansion ratio of the engine, and therefore its thermal efficiency. The reduced negative pressure swing is also of benefit in various ways, one important attainment being a reduction of the tendency for fire blowout under attenuated pressure conditions such as in flying at high altitude.

A number of embodiments of the invention have been described for illustrative purposes, but it will be understood that these are merely representative of the invention in several simple forms, and that various changes in design and arrangement, as well as application to various other types of resonant acoustic heat engines, may be made without departing from the spirit and scope of the appended claims. Among other obvious applications, it may, for example, be applied to the various types of engine disclosed in my copending application Ser. No. 157,740, filed April 24, 1950.

I claim:

1. In an acoustic burner, the combination of: a housing system providing a gas conduit and forming a resonant acoustic guide for a fundamental frequency acoustic pattern in the gas body within said housing system, which acoustic pattern has high impedance and low impedance regions spaced longitudinally of said gas conduit, a combustion chamber in said housing system at a high impedance region of said fundamental frequency acoustic pattern, said fundamental acoustic pattern having alternating positive and negative pressure half cycles relative to a mean static pressure at said combustion chamber region of high acoustic impedance, means for feeding fuel and air into said combustion chamber, a combustion gas discharge port at a low impedance region of said acoustic pattern, and means for engendering a second harmonic frequency acoustic pattern in said housing system having a region of high acoustic impedance within said combustion chamber and having in said region alternating positive and negative pressure half cycles relative to said static mean pressure with said positive half cycles in phase with the positive half cycles of said fundamental acoustic pattern.

2. The subject matter of claim 1, wherein said means for engendering said second harmonic frequency acoustic pattern comprises an air intake port in said housing system located at a low impedance region of said second harmonic frequency acoustic pattern.

3. The subject matter of claim 1, wherein said means for engendering said second harmonic comprises an air intake conduit means opening into said combustion chamber and having a length in the range of one-quarter wavelength for the second harmonic frequency acoustic pattern in said housing system.

4. The subject matter of claim 1, wherein said means for generating said second harmonic frequency acoustic pattern comprises a wave reflector.

5. The subject matter of claim 1, wherein said means for generating said second harmonic frequency acoustic pattern comprises a wave reflector located midway between pressure and velocity antinodes of the fundamental frequency acoustic pattern.

6. The subject matter of claim 1, wherein said means for generating said second harmonic frequency acoustic pattern comprises a reflector pipe having a length of one-quarter wavelength of the second harmonic wave, closed at one end and open at the other disposed with its open end exposed to a low impedance region of said fundamental frequency acoustic wave pattern.

7. Apparatus of the character described which includes: a resonant fluid housing forming an acoustic cavity for a fundamental frequency standing wave and a conduit for a fluid stream, a fluid discharge opening leading from said conduit, said cavity, when acoustically excited at fundamental frequency forming a guide for said fundamental standing wave, having a velocity anti-node adjacent said fluid discharge opening and a pressure anti-node region upstream of said conduit from said velocity anti-node, continuously open air intake conduit means opening into said housing at a junction point in the general region of said pressure anti-node, and means for supplying fuel to form a combustible mixture with said air for periodic combustion in said pressure anti-node region to excite said standing wave, said air intake conduit means having at its junction with said housing an acoustic impedance for the frequency of said fundamental standing wave in said resonant housing which is substantially as high as the acoustic impedance of the resonant housing at said point of junction for said fundamental frequency, and having also an acoustic impedance for the frequency of a second harmonic standing wave in said housing which is substantially as high as the acoustic impedance of the resonant housing at said point of junction for the frequency of said second harmonic.

8. Apparatus of the character described which includes: a resonant fluid housing forming an acoustic cavity for a fundamental frequency standing wave and a conduit for a fluid stream, a fluid discharge opening leading from said conduit, said cavity when acoustically excited at fundamental frequency forming a guide for said fundamental standing wave, having a velocity anti-node adjacent said fluid discharge opening and a pressure anti-node region upstream of said conduit from said velocity anti-node, a plurality of separate continuously open air intake conduits opening into said housing in the general region of said pressure anti-node, and means for supplying fuel to form a combustible mixture with said air for periodic combustion in said pressure anti-node region to excite said standing wave, one of said air intake conduits having at its junction with said housing an acoustic impedance for the frequency of said fundamental frequency standing wave which is substantially as high as the acoustic impedance of the resonant housing for that frequency at said point of junction, and another of said air intake conduits having at its junction with said housing an acoustic impedance for the frequency of the second harmonic which is substantially as high as the acoustic impedance of the resonant housing for the frequency of the second harmonic at said point of junction.

9. The subject matter of claim 8 wherein said one air intake conduit has a length of the order of a quarter wavelength for the frequency of the fundamental standing wave, and said other air intake conduit has a length of the order of one quarter wavelength for the frequency of said second harmonic.

10. Apparatus of the character described which includes: a resonant fluid housing forming an acoustic cavity for a fundamental frequency standing wave and a conduit for a fluid stream, a fluid discharge opening leading from said conduit, said cavity when acoustically excited at fundamental frequency forming a guide for said fundamental standing wave, having a velocity anti-node adjacent said fluid discharge opening and a pressure anti-node region upstream of said conduit from said velocity anti-node, a continuously open air intake conduit opening into said housing in the general region of said pressure anti-node, and means for supplying fuel to form a combustible mixture with said air for periodic combustion in said pressure anti-node region to excite said standing wave, said air intake conduit having air intake port means so spaced from said junction with said housing as to give said conduit an acoustic impedance for the frequency of said fundamental standing wave, at its junction with the conduit, which is substantially as high as the acoustic impedance of the resonant housing for that frequency at said point of junction, and having also air intake port means so spaced from said junction with said housing as to give said conduit an acoustic impedance for the frequency of the second harmonic, at its junction with said conduit, which is substantially as high as the acoustic impedance of the resonant housing for the frequency of the second harmonic at said point of junction.

11. The subject matter of claim 10 wherein the first mentioned air intake port means is spaced from the point of junction of the air intake conduit with the housing by a distance of the order of a quarter wavelength of the fundamental standing wave, and the second mentioned air intake port means is spaced from the point of junction of the air intake conduit with the housing by a distance of the order of a quarter wavelength of said second harmonic.

12. Apparatus of the character described which includes: a resonant fluid housing forming an acoustic cavity for a fundamental frequency standing wave and a conduit for a fluid stream, a fluid discharge opening leading from said conduit, said cavity when acoustically excited at fundamental frequency forming a guide for

said fundamental standing wave, having a velocity anti-node adjacent said fluid discharge opening and a pressure anti-node region upstream of said conduit from said velocity anti-node, an air intake conduit opening continuously into said housing in the general region of said pressure anti-node, means for supplying fuel to form a combustible mixture with said air for periodic combustion in said pressure anti-node region to excite said standing wave, said air intake conduit having continuously open air intake port means spaced from the point of junction of the conduit with the housing by a distance of the order of a quarter wavelength of a second harmonic wave in said conduit, and a check-valved air intake port means in said air intake conduit spaced from the point of junction of the conduit with the housing by a distance of the order of a quarter wavelength of the fundamental frequency standing wave in said conduit.

No references cited.