

- [54] **PRESSURE WAVE MIXING**
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[73] Assignee: **Energy Sciences Incorporated**, El Segundo, Calif.
[22] Filed: **Jan. 12, 1972**
[21] Appl. No.: **217,124**

Related U.S. Application Data

- [63] Continuation-in-part of Ser. Nos. 855,321, Sept. 4, 1969, abandoned, and Ser. No. 85,911, Nov. 2, 1970, abandoned, and Ser. No. 111,995, Feb. 2, 1971, and Ser. No. 158,915, July 1, 1971, and Ser. No. 189,206, Oct. 14, 1971, abandoned.
[52] **U.S. Cl.**..... **116/137 A, 239/102**
[51] **Int. Cl.**..... **B06b 3/00**
[58] **Field of Search**..... **116/137 A, 65, 70, 137 R; 123/191 B; 137/81.5; 235/201; 340/15; 239/4, 8, 102; 73/357, 357 A**

References Cited

UNITED STATES PATENTS

2,019,596	11/1935	Broden.....	116/137 R
2,364,987	12/1944	Lee.....	261/78
2,755,767	7/1956	Lavavasseur.....	116/137 A
3,230,923	1/1966	Hughes.....	116/137 A
3,368,577	2/1968	Otsap.....	137/810
3,432,804	3/1969	Beeken.....	340/15
3,554,443	1/1971	Hughes.....	116/137 A X
3,581,992	6/1971	Hughes.....	239/102
3,600,612	8/1971	Beeken.....	116/137 A X
3,613,452	10/1971	Zoerb.....	73/357 X

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[57] **ABSTRACT**

The propagating range and/or energizing capability of pressure waves are enhanced by mixing pressure waves from a plurality of sources. The wavelengths of the pressure waves and the physical dimensions of the mixing arrangement are related to each other. In a first embodiment, coherent sonic waves are coupled to the inlets of a plurality of passages having cross-sectional dimensions related to the wavelength of the sonic waves, and the sonic waves emanating from the outlets of the passages are combined. The outlets of adjacent passages are preferably spaced from each other a distance related to the wavelength. In a second embodiment, coherent shock waves produced by two supersonic nozzles are combined at a point of intersection; the nozzles are dimensioned to produce shock waves having related wavelengths. In a third embodiment, coherent shock waves produced by a supersonic nozzle and the pressure pulses characteristic of a simple orifice are combined at a point of intersection; the orifice is dimensioned so the wavelengths of the shock waves and the pressure pulses are related. In the second and third embodiments, the point of intersection is preferably spaced from the sources a distance that is related to the wavelengths. In a fourth embodiment, coherent shock waves produced by a supersonic nozzle and pressure waves characteristic of a simple orifice are combined in a resonant cavity having rectangular cross-sectional dimensions that are related to the wavelengths.

40 Claims, 15 Drawing Figures

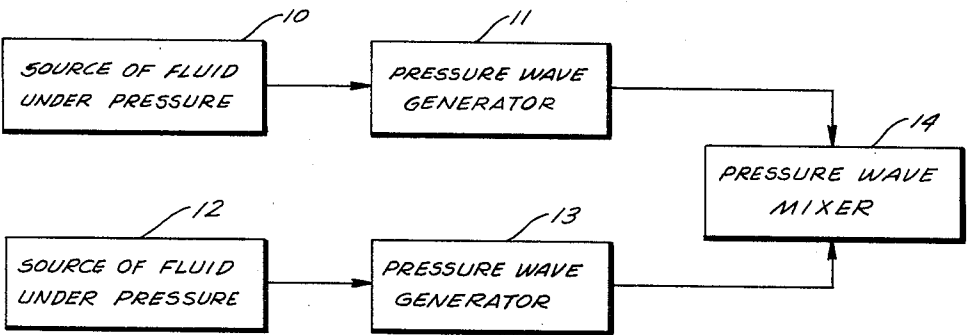


FIG. 1

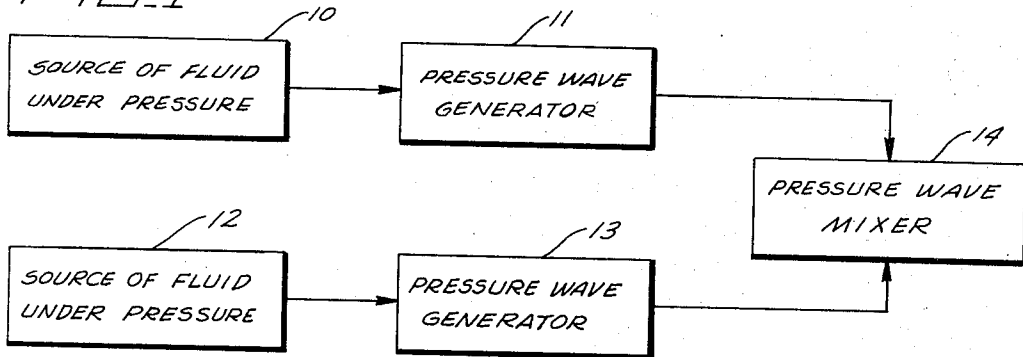


FIG. 2A

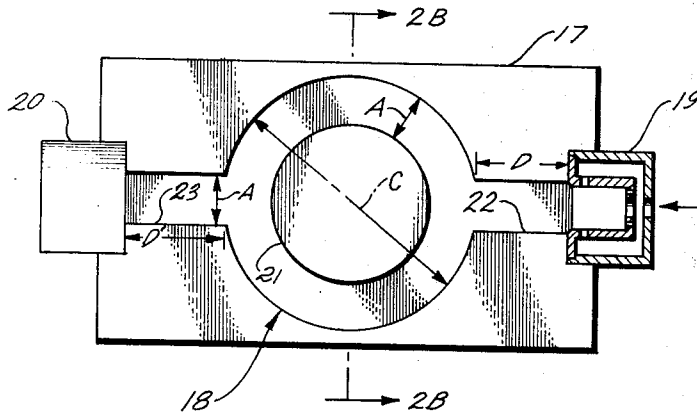


FIG. 2B

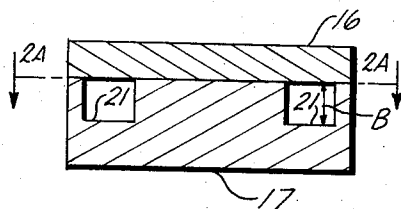


FIG. 3A

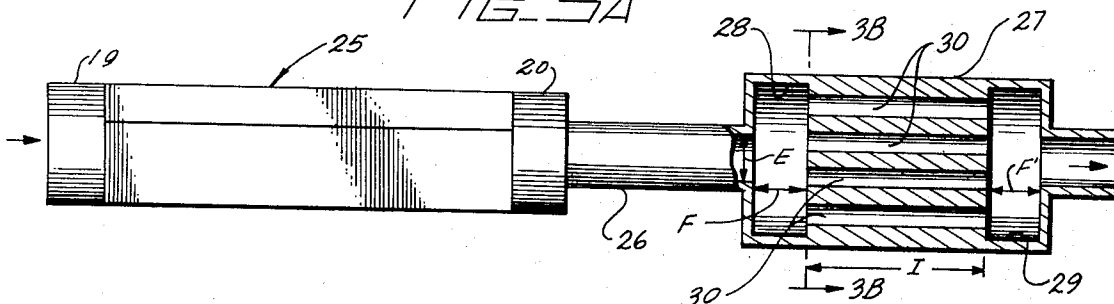


FIG. 3B

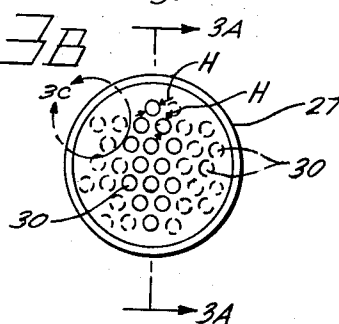


FIG. 3C

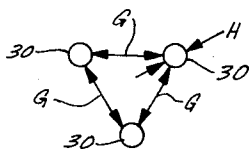


FIG. 8

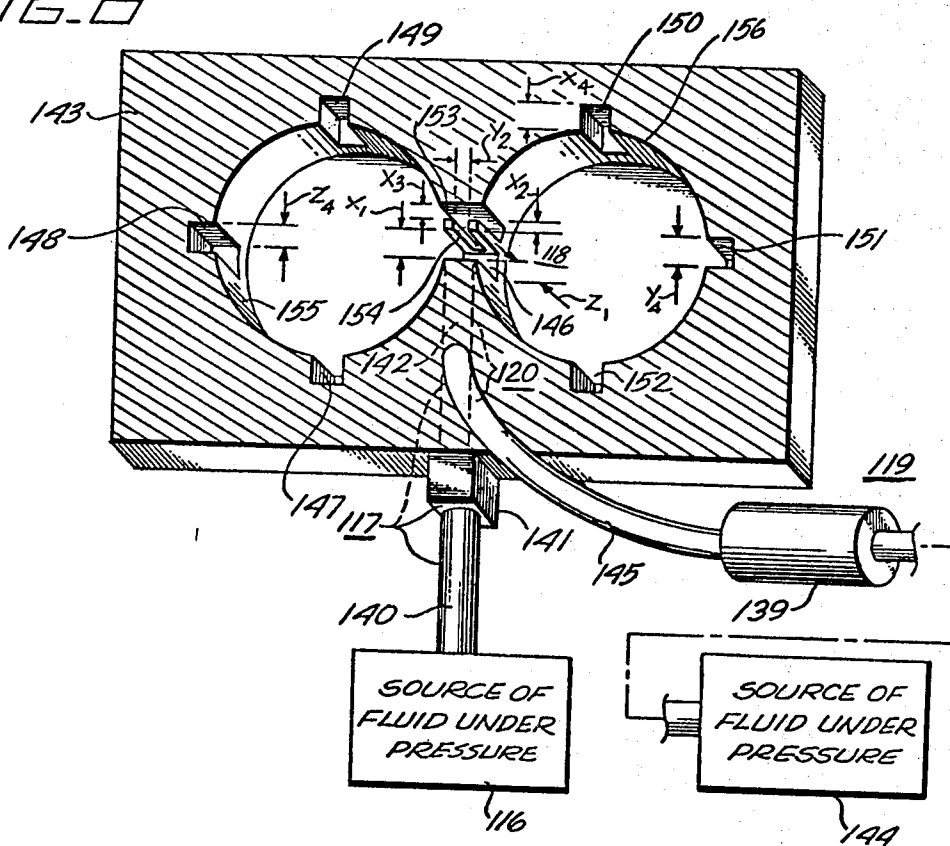


FIG. 4

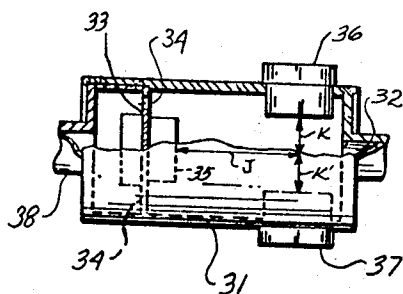


FIG. 5B

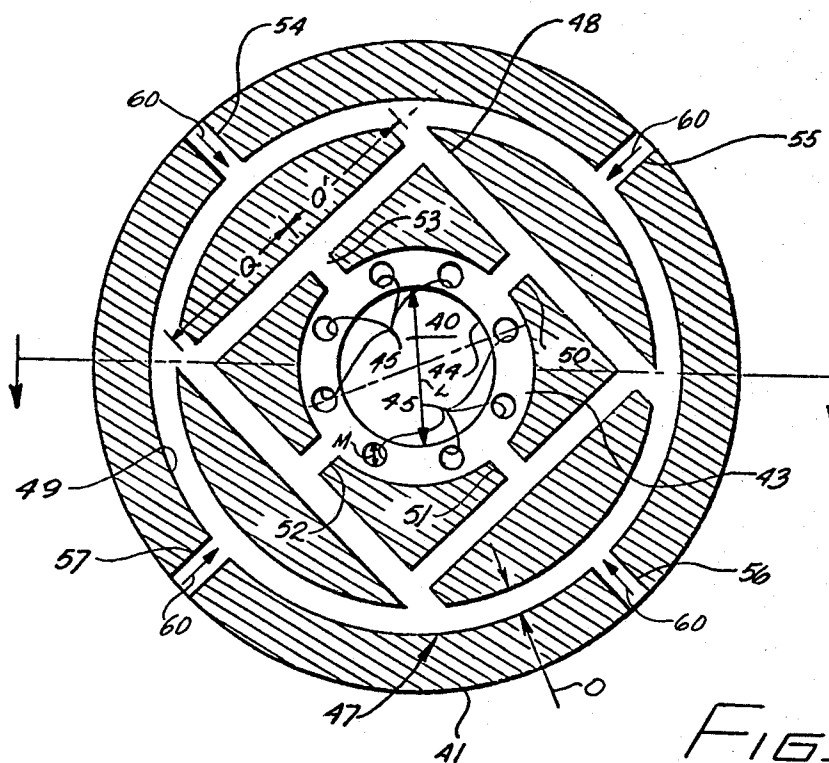


FIG. 5A

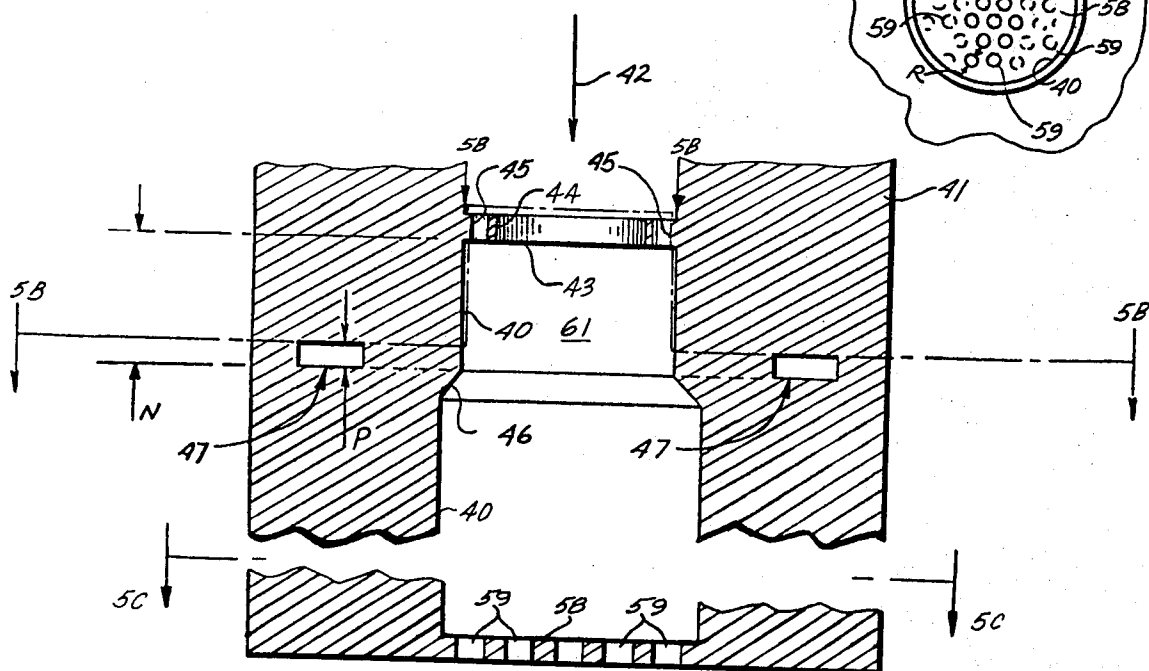


FIG. 5C

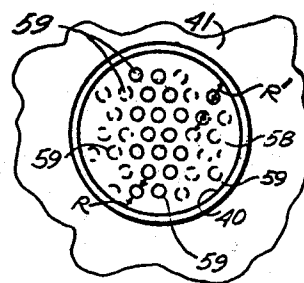


FIG. 6

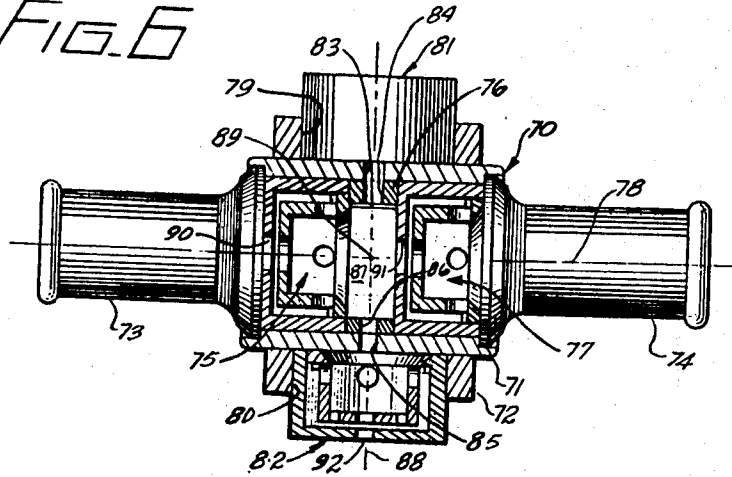


FIG. 7A

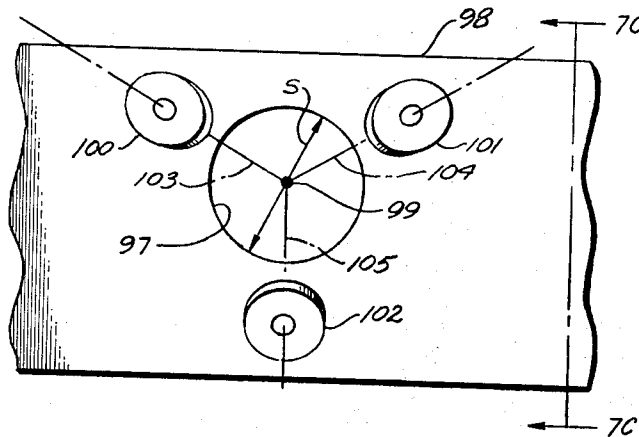


FIG. 7B

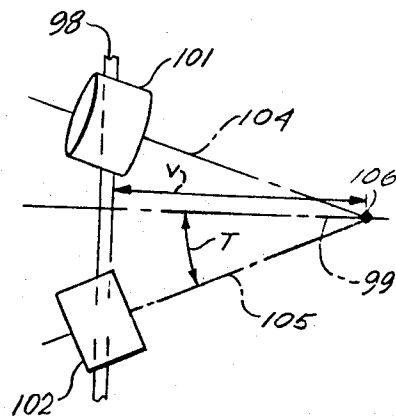
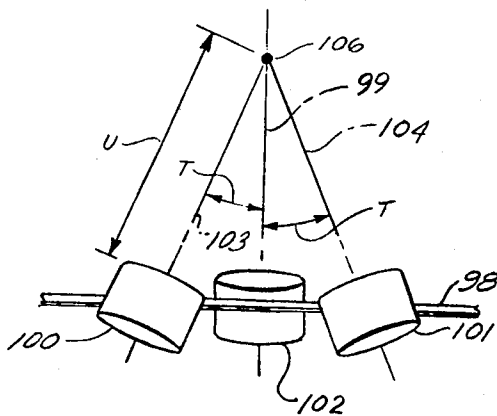


FIG. 7C

PRESSURE WAVE MIXING

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part of the following applications, the contents of which are incorporated herein by reference: Ser. No. 855,321, filed Sept. 4, 1969, now abandoned; Ser. No. 85,911, filed Nov. 2, 1970, now abandoned; Ser. No. 111,995, filed Feb. 2, 1971; Ser. No. 158,915, filed July 1, 1971; and Ser. No. 189,206, filed Oct. 14, 1971, now abandoned.

BACKGROUND OF THE INVENTION

This invention relates to the enhancement of the propagating range and/or energizing capability of pressure wave energy and, more particularly, to apparatus and method for combining pressure waves to obtain such enhancement.

My U.S. Pat. No. 3,554,443, which issued on Jan. 12, 1971, discloses a shock wave generating cell in which a converging-diverging supersonic flow nozzle is formed in a cylindrical passage by fluid boundary layers that adjust the effective nozzle dimensions to compensate for pressure changes. The boundary layers are developed by a number of holes leading into the cylindrical passage. The hole diameters and the dimensions of the cell are selected so the component wavelengths of the pressure waves generated in the cell are multiples and submultiples of each other.

In my copending application, Ser. No. 189,206, filed Oct. 14, 1971, there are disclosed a number of arrangements of resonant cavities that are particularly effective in combination with the shock wave generating cell referenced in the preceding paragraph. The sonic waves generated in the resonant cavities have a propagating range and energizing capability that far exceed expectations based on experience with previous pressure wave generators.

Pressure wave generators in general, and the pressure wave generators described in the two preceding paragraphs in particular, find a large number of industrial applications, such as the atomization of a fluid into a finely suspended state. For example, my copending application, Ser. No. 158,915, filed July 1, 1971, which matured into Pat. No. 3,730,160 on May 1, 1973, teaches the use of pressure waves to energize the combustible mixture in an internal combustion engine in a manner that achieves a substantial reduction of all the major engine pollutants, improved engine performance, and reduced fuel consumption.

SUMMARY OF THE INVENTION

The invention relates to a novel technique for combining pressure wave energy from a plurality of sources in a manner that enhances the propagating range and/or energizing capability of the pressure wave energy. The term "mixing" has been coined in this specification to describe the pressure wave combining technique because of its analogy to electrical mixing or heterodyning. The wavelength distribution of the energy is apparently changed, i.e., energy from a source of pressure waves having a large wavelength is translated or converted to energy having a smaller wavelength, which may be more effective for energizing purposes.

Briefly, pressure waves having related wavelengths are combined in one of a number of different arrangements involving physical dimensions related to the wavelengths. My U.S. Pat. No. 3,531,048 discloses a plurality of supersonic nozzles massed together to sum the energy components from the individual nozzles; but this arrangement of nozzles does not exhibit the relationship between its physical dimensions and wavelength that achieves the mixing action of the invention.

Although the invention may take many different forms, four important specific embodiments are illustrated in the specification. In a first embodiment, coherent sonic waves are coupled to the inlets of a plurality of passages having cross-sectional dimensions related to the wavelength of the sonic waves, and the sonic waves emanating from the outlets of the passages are combined. The outlets of adjacent passages are preferably spaced from each other a distance related to the wavelength. In a second embodiment, coherent shock waves produced by two supersonic nozzles are combined at a point of intersection; the nozzles are dimensioned to produce shock waves having related wavelengths. In a third embodiment, coherent shock waves produced by a supersonic nozzle and the pressure pulses characteristic of a simple orifice are combined at a point of intersection; the simple orifice is dimensioned so the wavelengths of the shock waves and the characteristic pressure pulses are related. In the second and third embodiments, the point of intersection is preferably spaced from the sources a distance that is related to the wavelengths. In a fourth embodiment, coherent shock waves produced by a supersonic nozzle and pressure waves characteristic of a simple orifice are combined in a resonant cavity having rectangular cross-sectional dimensions that are related to the wavelengths.

It has been found that a very effective wavelength for the pressure waves and a cross section for the passages, orifices, and resonant cavities involves a dimension in the range of 0.170 to 0.195 inches, a multiple or submultiple thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

The features of specific embodiments of the best mode contemplated for carrying out the invention are illustrated in the drawings, in which:

FIG. 1 is a schematic block diagram depicting the elements of the invention;

FIGS. 2A and 2B are, respectively, a top sectional view and a side sectional view of one version of a first embodiment of the invention;

FIGS. 3A and 3B are, respectively, a front, partially sectional view and a side sectional view of another version of the first embodiment of the invention incorporating in part the apparatus of FIGS. 2A and 2B;

FIG. 3C is an enlargement of a portion of FIG. 3B illustrating the distance between adjacent tubes;

FIG. 4 is a front, partially sectional view of another version of the pressure wave mixer of the first embodiment;

FIGS. 5A, 5B, and 5C are, respectively, a front sectional view, a top sectional view through a first plane, and a top sectional view through a second plane of another version of the first embodiment of the invention;

FIG. 6 is a front, partially sectional view of a second embodiment of the invention;

FIGS. 7A, 7B, and 7C are, respectively, a front elevation view, a top plan view, and a side sectional view of a third embodiment of the invention; and

FIG. 8 is a top sectional view of a fourth embodiment of the invention.

DETAILED DESCRIPTION OF THE SPECIFIC EMBODIMENTS

As used in this specification, the term "pressure pulses" means periodic positive pressure pulses that are predominately unipolar, i.e., the pressure at a given point in space pulsates between ambient pressure and a pressure higher than ambient pressure, so compression of the fluid molecules repeatedly occurs, although between the compressive pulses slight negative pulses may occur. Coherent pressure pulse energy consists of pressure pulses having the same wavelength or a number of component wavelengths that are multiples or submultiples of each other, i.e., that are multiply related. Shock waves are pressure pulses produced as a result of supersonic fluid flow. The term "sonic waves" means periodic bipolar pressure waves, i.e., the pressure at a given point in space sinusoidally oscillates between a pressure higher than ambient and a pressure lower than ambient, so compression and rarification of the fluid molecules alternately occur. Coherent sonic wave energy consists of sonic waves having the same wavelength or a number of component wavelengths that are multiply related. The term "pressure waves" is generic to pressure pulses and sonic waves. The term "coherency" as used herein does not exclude the presence of some pressure wave energy at component wavelengths that are not multiply related to the remaining component wavelengths or to the presence of some random pressure wave energy, analogous to background noise; rather the term "coherent" is used to designate that a substantial amount of pressure wave energy at multiply related wavelengths is present. As used herein, the term "wavelength" of pressure waves may refer to pressure waves in which the energy is distributed at a number of component wavelengths, in which case "wavelength" means one of such component wavelengths.

In FIG. 1, which depicts the invention in general terms, a source 10 of fluid under pressure is coupled to a pressure wave generator 11, and a source 12 of fluid under pressure is coupled to a pressure wave generator 13. Generators 11 and 13 are designed to produce coherent pressure waves each having the same or multiply related wavelengths. The pressure waves produced by generators 11 and 13 are coupled to a pressure wave mixer 14, where they combine in a manner that enhances the propagating range and/or energizing capability of the resultant pressure waves. The pressure wave mixing action is analogous to electrical mixing or heterodyning in that a transfer of the energy distribution from one wavelength to another apparently takes place when pressure waves having different wavelengths are so combined. For a discussion of the electric properties of pressure waves generated by the type of device contemplated by the invention, see my co-pending application Ser. No. 189,206, which is incorporated herein by reference. Further, in some embodiments of the invention there is apparently an amplification of the intensity of the pressure waves and a realign-

ment of the energy at the original wavelength or component wavelengths. In any case, the propagating range and/or energizing capability of the pressure waves are increased substantially.

By way of example, sources 10 and 12 could be air at a gage pressure in the range of 1 to 20 psi and mixer 14 could communicate with the atmosphere to establish a pressure drop across generators 11 and 13. Alternatively, sources 10 and 12 could be atmospheric air and mixer 14 could be in communication with a subatmospheric environment, e.g., the intake system of an internal combustion engine. If sources 10 and 12 are the same fluid at the same pressure, they can obviously be replaced by a single source. Two sources are represented in FIG. 1 to encompass the general case in which different fluids and/or different pressures may be involved.

Some aspects of the invention are based upon the fact that pressure pulses are produced when a fluid passes through a simple orifice. These pressure pulses are characteristic of the orifice in that their wavelength is directly related to the cross-sectional dimensions of the orifice (diameter of a circular orifice and side of a square orifice) and inversely related to the velocity of the fluid flowing through the orifice. Although these characteristic pressure pulses are often imperceptible, particularly at subsonic velocities, their presence is manifested when they are combined with other, perceptible pressure waves having a related wavelength, because the resultant pressure wave energy is intensified i.e. amplified. The shock wave generating cell disclosed in my U.S. Pat. No. 3,554,443 utilizes the characteristic pressure pulses produced in air flowing through a number of holes leading into the cell. The holes are dimensioned so the characteristic pressure pulses are all related in wavelength to the shock waves produced by the cell. Consequently, the energizing capability of the resultant pressure waves produced in the nozzle is greatly enhanced. The disclosures of my U.S. Pat. No. 3,554,443, my U.S. Pat. No. 3,531,048, which issued Sept. 29, 1970, and application Ser. No. 189,206, are incorporated herein by reference.

Different forms of generators 11 and 13 and mixer 14 are illustrated below in connection with four specific embodiments of the invention. In the first embodiment, coherent sonic waves are coupled to the inlet of a plurality of closely spaced passages each having a cross-sectional dimension related to the sonic wave wavelength. The outlets of adjacent passages are preferably spaced from each other a distance related to the wavelength. The passages fed by the sonic wave energy correspond to pressure wave generators 11 and 13 in FIG. 1, and the outlets of the passages where the pressure waves emerge and combine correspond to mixer 14 in FIG. 1. In the second embodiment, the outlets of a plurality of supersonic nozzles are directed so the shock waves produced by the respective nozzles converge at a point of intersection. The nozzles, which are designed to produce shock waves having related preferably equal wavelengths, correspond to pressure wave generators 11 and 13 in FIG. 1, and the convergently arranged outlets of the nozzles correspond to mixer 14 in FIG. 1. In the third embodiment, the outlet of a supersonic nozzle and a simple orifice are directed so the shock waves produced by the nozzle and the pressure pulses characteristic of the orifice converge at a point of intersection. The nozzle and the orifice are designed

so the wavelength of the shock waves is related to, and preferably substantially smaller than, the wavelength of the characteristic pressure pulses. The nozzle and the simple orifice correspond, respectively, to generators 11 and 13 in FIG. 1, and the convergently arranged outlet of the nozzle and the orifice correspond to mixer 14 in FIG. 1. In the third and fourth embodiments, the distances from the nozzles and orifices to the point of intersection are preferably related to the pressure wave wavelengths. In the fourth embodiment, the outlet of a supersonic nozzle and a simple orifice are connected to a resonant cavity having a cross-sectional dimension that is related to the wavelength of the shock waves produced by the nozzle and to the pressure pulses characteristic of the orifice. The nozzle and the simple orifice correspond to generators 11 and 13, and the resonant cavity corresponds to mixer 14.

In FIG. 2A and 2B, which depict one version of the first embodiment, rectangular metallic plates 16 and 17 are clamped together by means not shown. A network 18 of channels formed in plate 17 couples the outlet of a shock wave generating cell 19, which is affixed to one end of plate 17, to the inlet of a shock wave generating cell 20, which is affixed to the other end of plate 17. The term "shock wave generating cell" as used throughout this specification means the device described in my U.S. Pat. No. 3,554,443; when reference is made to a shock wave generating cell in this specification, it is assumed the device has the dimensions stated in my U.S. Pat. No. 3,554,443 except for cell inlet hole 36, which is 0.172 inches. For these dimensions, component wavelengths are multiples or submultiples of a basic wavelength in a range of 0.170 to 0.195 inches, depending upon the source pressure within a range of 1 to 20 psi. For the purpose of discussion, a nominal value of 0.180 inches will be presumed for the basic wavelength of the cell in the exemplary dimensions given in the following embodiments and arrangements. As illustrated in FIG. 2A, network 18 comprises a circular channel 21 and straight channels 22 and 23 extending from opposite sides of channel 21 to the exterior of plate 17. Channel 22 connects the outlet of cell 19 to channel 21, and channel 23 connects channel 21 to the inlet of cell 20. Channels 21, 22, and 23 all have rectangular, preferably, square, cross sections with a width A and a height B related to the basic wavelength of cells 19 and 20 (e.g., $A, B = 0.180$ inches). The outer diameter C of circular channel 21 is preferably related to the width A and the height B of the channels (e.g., $C = 0.900$ inches). The lengths D and D' of straight channels 22 and 23, respectively, are also preferably related to the width A and height B (e.g., $D, D' = 0.360$ inches). Thus, the A, B, C, D, and D' dimensions are significant. Channels 21, 22, and 23 could be formed by grinding a groove out of the surface of plate 17 adjacent to plate 16. Air or other fluid flows through cell 19, network 18, and cell 20 in the direction of the arrow in FIG. 2A i.e. from right to left and coherent sonic waves emanate from cell 20 with the fluid. In this version of the first embodiment, the holes in cell 20 (assigned reference numerals 18, 20, and 22 in my U.S. Pat. No. 3,554,443) are the passages, and the sonic waves are supplied by cell 19 via network 18. Since the dimensions of cells 19 and 20 are the same, the prescribed dimensional relationship between the wavelength of the sonic waves and the cross section of the passages is present. This version of the first embodi-

ment, i.e., the device shown in FIGS. 2A and 2B, is, as a unit, a very effective coherent sonic wave generator suitable for use as the basic building block for larger systems.

In the version of the first embodiment shown in FIGS. 3A, 3B and 3C, the device of FIG. 2 serves as a sonic wave generator 25. In FIG. 3A the device is turned around with respect to FIG. 2A in that air or other fluid flows from left to right, i.e., in the direction of the arrows, cell 19 is on the left, and cell 20 is on the right. A conduit 26 couples generator 25 to a cylindrical housing 27. Conduit 26 preferably has a circular cross section with a diameter E related to the wavelength of the sonic waves produced by generator 25 (e.g., $E = 0.180$ inches). Housing 27 has a disc shaped manifold 28 at one end, a disc shaped manifold 29 at the other end, and a plurality of elongated parallel tubes 30 interconnecting manifolds 28 and 29. Manifolds 28 and 29, which have a depth F and F', respectively, related to the wavelength of the coherent sonic waves produced by generator 25 (e.g., $F, F' = 0.180$ inches), serve as resonant cavities. Tubes 30 each have a cross-sectional diameter H and a length I that are related to the wavelength of the sonic waves produced by generator 25 (e.g., $H = 0.090$ inches and $I = 1.080$ inches). Manifold 28 distributes the sonic wave energy from generator 25 to the inlets of tubes 30 and the sonic wave energy emanating from the outlets of tubes 30 combines and mixes in manifold 29 to enhance its energizing capability. The distance G between adjacent tubes is small and preferably related to the wavelength of the sonic waves (e.e., $G = 0.090$ inches). As a result, the mixing action of the sonic waves emanating from tubes 30 is further intensified because the distance of the points of combination from the outlet of each tube is related to the wavelength of the sonic waves. The E, F, F', G, H, and I dimensions are significant. In this version of the first embodiment, tubes 30 correspond to the passages and manifolds 28 and 29 serve as resonant cavities to further enhance the energizing capability of the sonic waves passing through housing 27. This version of the first embodiment is particularly well suited for applications in which a pressure wave generator must be placed a large distance from the point where the energy is to be utilized. In such case, one or more units identical to housing 27 are placed at intervals along the conduit that couples the pressure wave energy from the generator to the point of utilization to amplify and regenerate, i.e., re-establish the coherency of, the pressure waves. As an alternative to the circular arrangement of tubes in a cylindrical housing, the tubes could be placed in a straight line within a flat plate, and the manifolds at the ends of the tubes could be rectangular cavities formed within the plate.

FIG. 4 depicts another version of the first embodiment. A conduit 38 connects sonic wave generator 25 of FIG. 3, which is not shown in FIG. 4, to a cylindrical housing 31. An exit 32 is formed at the other end of housing 31. The interior of housing 31 is divided by a baffle 33 having arcuate slots 34. A shock wave generating cell 35 is mounted to baffle 33 with its inlet facing conduit 38 and its outlet facing exit 32. Shock wave generating cells 36 and 37 are affixed to the sidewall of housing 31 so their inlets communicate with the exterior of housing 31 and their outlets are axially aligned with each other inside housing 31. Air or other fluid under pressure flows from the exterior of housing 31

through cells 36 and 37 to produce shock waves at their outlets. The arrangement of FIG. 4 including exemplary dimensions is disclosed in detail, but not claimed, in application Ser. No. 158,915. Assuming that the wavelength of the sonic waves coupled to housing 31 is 0.180 inches, the dimensions of cells 35, 36, and 37 are as specified in my U.S. Pat. No. 3,554,443. Some of the sonic wave energy passes through the holes in cell 35 and is mixed in its cylindrical passage in the same manner as cell 20 in FIG. 2; the remainder is coupled through slots 34, bypassing cell 35.

The pressure waves emanating from cells 35, 36, and 37 are directed to converge at a point of intersection near exit 32. The distance J from the outlet of cell 35 to the point of intersection, the distance K from the outlet of cell 36 to the point of intersection, and the distance K' from the outlet of cell 37 to the point of intersection are all preferably related to the wavelength of the sonic waves. The reason for this dimensional relationship is discussed below in connection with the second embodiment of the invention.

In FIGS. 5A, 5B, and 5C, another version of the first embodiment is shown. A central passage 40 is formed in a cylindrical housing 41. A source of fluid under pressure is connected to passage 40 so the fluid flows in the direction of an arrow 42. A baffle 43, which is shown as an integral part of housing 41 but which could be a separate insert, is disposed across passage 40 near its upstream end. Baffle 43 has a large central hole 44 and an even plurality of small holes 45 annularly arranged around hole 44. The diameter L of hole 44 is related to the diameter M of holes 45 (e.g., $L = 1.080$ inches and $M = 0.180$ inches). In general, hole 44 is made as large as possible to minimize the restriction of the fluid flow imposed by baffle 43, while maintaining the dimensional relationship between the diameters of holes 44 and 45. A 45° countersink 46 is formed in distance N downstream of baffle 43. A network 47 of channels having a rectangular, preferably square, cross section is formed in housing 41. Network 47 extends along an imaginary plane that crosses passage 40 adjacent to the upstream side of countersink 46. It comprises a square channel 48, a circular channel 49 that circumscribes and communicates with the corners of square channel 48, and channels 50, 51, 52, and 53 that connect the midpoints of the respective sides of square channel 48 with passage 40.

The width O and height P of the channels of network 47 and the distances Q and Q' between the junctions of circular channel 49 with the corners of square channel 48 and the junctions of square channel 48 with connecting channels 50 through 53 are related to holes 44 and 45 (e.g., $O, P = 0.180$ inches and $Q, Q' = 1.080$ inches). Conduits 54, 55, 56, and 57 connect the source of fluid under pressure to network 47 so the fluid flows in the direction of arrows 60. A shock wave generating cell is preferably disposed in the path from the source to each of conduits 54, 55, 56, and 57 to pre-energize the fluid before it enters network 47. Conduits 54 through 57, which are spaced at 90° intervals around circular channel 49, each preferably have either a circular cross section with a diameter or a square cross section with side dimensions equal to the O and P dimensions. The distance N, although not critical, is preferably related to the other dimensions (e.g., $N = 0.540$ inches). Hole 44, holes 45, connecting channels 50 through 53, and countersink 46 are analogous to the

corresponding elements of the shock wave generating cell disclosed in my U.S. Pat. No. 554,443. The fluid flowing through connecting channels 50 through 53 and through holes 45 forms a converging-diverging boundary layer in the same manner as the corresponding holes in the cell disclosed in my U.S. Pat. No. 3,554,443. Thus, the fluid stream passing through hole 44 is accelerated as it flows through passage 40 downstream of baffle 43. Circular channel 49, square channel 48, connecting channels 50 through 53, and conduits 54 through 57 are analogous, respectively, to circular channel 212, triangular channel 213, connecting channels 217 through 219, and conduit 225 in FIG. 21 in application Ser. No. 158,915. Sonic waves are induced in the fluid stream supplied to network 47 by conduits 54 through 57. The sonic waves are coupled by connecting channels 50 through 53, to passage 40 where they stabilize the converging-diverging boundary layer and interact with the accelerating stream of fluid passing through hole 44. As a result, there is formed a sonic wave generator, designated 61, which completely energizes the fluid stream traveling through passage 40 and radiates sonic waves having a high energizing capability through passage 40.

The stabilizing effect that the sonic wave energy exercises on the boundary layer downstream of baffle 43 is very significant because it removes the size restriction on the nozzle dimensions and thereby permits large quantities of fluid to be thoroughly energized. In contrast, if the cell disclosed in my U.S. Pat. No. 3,554,443 is increased appreciably in size, the boundary layer tends to separate, thicken, and generally deteriorate.

Baffle 58, which is shown as an integral part of housing 41, but which could be a separate insert, is disposed across passage 40 at its downstream end an arbitrary distance from sonic wave generator 61. Baffle 58 has a plurality of circular perforations 59 with the same diameter R. The diameter R and the spacing R' between adjacent perforations are related to the dimensions of sonic wave generator 61 and therefore to the sonic waves it generates (e.g., $R, R' = 0.360$ inches). In short, perforations 59 are the passages of the first embodiment and the pressure waves are supplied by generator 61. As the pressure wave energy traveling through passage 40 leaves perforations 59, it combines at a distance $R'/2$ from each of passages 40 and is thereby amplified and regenerated to increase its effective propagating range. A large volume of fluid can be energized and transmitted long distances by providing a number of perforated baffles such as baffle 58 at spaced intervals along passage 40 downstream of a sonic wave generator such as generator 61. The L, M, O, P, Q, Q', R, and R' dimensions are significant.

When the passages of the first embodiment are much shorter than a wavelength of the pressure waves, as in the versions of FIGS. 2, 4, and 5, the length of the passages is not significant; but when the passages are not short relative to a wavelength, as in the version of FIG. 3, the length of the passages is significant.

In FIG. 6, which exemplifies the second embodiment, a housing 70 comprises a cylindrical tube 71, a cylindrical outer jacket 72, and tubular fittings 73 and 74. Fittings 73 and 74 are fixed to tube 71 by swaging or other means. Jacket 72, which surrounds tube 71, has a force fit therewith. A shock wave generating cell 75, an annular spacer 76, and a shock wave generating cell 77

are disposed within tube 71 along its cylindrical axis 78 in abutting relationship between the ends of fittings 73 and 74, as shown in FIG. 6. Thus, cells 75 and 77 and spacer 76 fit snugly inside housing 70 as a single cylindrical unit without being able to move. The space enclosed by spacer 76 between cells 75 and 77 comprises a resonant cavity 87. Cylindrical counterbores 79 and 80 are formed at diametrically opposite sides of jacket 72. Cylindrical shock wave generating cells 81 and 82 are maintained in counterbores 79 and 80, respectively, by force fits. A circular hole 83 through tube 71 and a circular hole 84 through spacer 76 couple cell 81 to cavity 87. A circular hole 85 through tube 71 and a circular hole 86 through spacer 76 couple cell 82 to cavity 87. Counterbores 79 and 80, cells 81 and 82, and holes 83 through 86 are all centered about a transverse axis 88 that is perpendicular to axis 78 and intersects axis 78 at a point 89 within cavity 87. The cell inlet hole of cells 81 and 82 is 0.088 inches. In other words, openings 90 and 91 of cells 75 and 77, respectively, are essentially twice as big in diameter as opening 92 of cell 82 and the corresponding opening of cell 81 (not shown).

Cavity 87 is cylindrical. The inside surface of spacer 76 defines the cylindrical side wall of cavity 87, the upstream end of the cover of cell 77 defines the reflective end wall of cavity 87, and axis 78 is the longitudinal axis of cavity 87. The distance along axis 78 from the upstream end of cavity 87 to intersection point 89 is X_1 , the distance along axis 78 from intersection point 89 to the downstream end of cavity 87 is X_2 , the distance along axis 88 from the side wall of cavity 87 at the point where hole 84 is formed to intersection point 89 is Y_1 , and the distance along axis 88 from the side wall of cavity 87 at the point where hole 86 is formed to intersection point 89 is Y_2 . (See FIG. 5 of application Ser. No. 111,995.) In the disclosed embodiment, cavity 87 is cylindrical and holes 84 and 86 are spaced midway between the ends of cavity 87. Thus, distances Y_1 and Y_2 are the same, their sum equalling the diameter of the cylinder, and distances X_1 and X_2 are the same, their sum equalling the length of the cylinder. The X_1 , X_2 , Y_1 , and Y_2 dimensions are related to the wavelength of the pressure pulses produced by cells 75, 77, 81, and 82 (e.g., X_1 , X_2 = 0.090 inches and Y_1 , Y_2 = 0.180 inches).

Holes 83 and 84 and holes 85 and 86 have a diameter, i.e., 0.090 inches, essentially equal to one-half the shock wave wavelength, so the shock waves from cells 81 and 82 are coupled to cavity 87 by holes 83 through 86 without appreciable attenuation. Thus, cells 81 and 82 have a virtual or apparent outlet at the side wall of cavity 87. The shock waves produced by cells 81 and 82 have vertices that propagate along transverse axis 88 to collide with the vertex of the shock waves produced by cell 75 at intersection point 89. The relationship of the distances X_1 , X_2 , $X_1 + X_2$, Y_1 , and Y_2 , which are significant, to the shock wave wavelength enhances the mixing action when the shock waves collide.

The device disclosed in FIG. 4 alone without any external source of pressure waves, such as generator 25, comprises another version of the second embodiment. If the distance J, K, and K' are related to the wavelength of the shock waves produced by cells 35, 36, and 37 (e.g., J = 0.900 inches and K, K' = 0.360 inches), the pressure pulses from cells 35, 36, and 37 mix in a

fashion similar to those from cells 75, 81, and 82 of FIG. 6.

In FIGS. 7A, 7B, and 7C there is shown a device that exemplifies the third embodiment. A large hole 97 is formed in a planar member 98 on an axis 99. Shock wave generating cells 100, 101, and 102 are mounted in member 98 on axes 103, 104, and 105, respectively. Axes 103 through 105 intersect axis 99 at a point 106. As depicted by the equidistant arrangement of the projection of axes 103, 104, and 105 in FIG. 7A, cells 100, 101, and 102 are spaced 120° apart with respect to the plane of hole 97. Axes 103, 104, and 105 each form an angle T with axis 99 (e.g., $T = 22.5^\circ$). The distance U from the outlet of each of cells 100, 101, and 102 to intersection point 106, the distance V from the center of hole 97 to point 106, and the diameter S of hole 97 are related to the wavelength of the shock waves produced by cells 100, 101, and 102 (e.g., S = 1.080 inches and U = 1.800 inches). Thus, the outlets of cells 100, 101, and 102 and the center of hole 97 are all located at radii of a sphere centered at point 106. The inlets of cells 100, 101, and 102 communicate with the side of member 98, shown in FIG. 7A. When a pressure drop is established from the inlet side of member 98 to the outlet side, air or other fluid passes through hole 97 and mixes at point 106 with the shock waves produced by cells 100, 101, and 102 as the air flows through them. Essentially all the air passing from the inlet side of member 98 to its outlet side is energized by virtue of the shock waves impinging and mixing at point 106. When the air flow through hole 97 approaches sonic velocity, the characteristic pressure pulses of hole 97 approach a multiple of the shock wave wavelength, and the mixing action is intensified. In addition to the essentially complete energization of the air flowing through member 98, the third embodiment has an additional major advantage, namely, that hole 97 permits more air to flow as the source pressure increases over the range of operation. In other words, although there is supersonic flow through cells 100, 101, and 102, flow through hole 97 is not choked. In summary, for low pressure drops flow through cells 100, 101, and 102 predominates and for high pressure drops flow through hole 97 predominates. Moreover, as the source pressure increases, the intensity of the shock waves from cells 100, 101, and 102 also increases, thereby providing the capability to energize the additional air flowing through hole 97.

One important application of the third embodiment is as an energizing unit within the air cleaner of an internal combustion engine. In this case, member 98 fits inside the filter element of the air cleaner and is annular in form and sealed so all the air passing through the filter element must pass through cells 100 through 102 and hole 97 in order to reach the inlet of the carburetor. Preferably, two other holes identical to hole 97 are spaced around member 98 at 120° intervals from hole 97, and each of the other holes are provided with three shock wave generating cells identical in arrangement to cells 100 through 102. In this environment, the third embodiment of the invention is particularly important because the unchoked flow through hole 97 permits sufficient air to flow into the carburetor to fulfill the engine needs at high acceleration; the large amount of air flowing through hole 97 continues to be energized by the convergence of shock waves from cells 100 through 102 at point 106. On the other hand, at idle and other

low flow conditions most of the air bypasses hole 97. Member 98 is annular because of the air cleaner application. If the third embodiment is to be employed in some other application, member 98 could have some other form.

In FIG. 8, a conduit 117, a pressure wave generator 119, a coupling 120, and a resonant cavity 118 are shown. Conduit 117 comprises an external pipe 140, a coupling 141, and an elongated passage 142 all having circular inside cross sections with equal diameters. Pipe 140 is connected by coupling 141 to elongated passage 142, which extends through a metallic plate 143. Plate 143 has holes 155 and 156 through it. Pressure wave generator 119 comprises a shock wave generating unit 139 having an inlet to which a source 144 of fluid under pressure is applied. Preferably, unit 139 comprises a pair of shock wave generating cells arranged in tandem with each other as disclosed in my application Ser. No. 13,977, filed Feb. 25, 1970, now abandoned. A tube 145 connects the outlet of unit 139 to passage 142 at a point intermediate its ends. Tube 145 has a circular cross section (e.g. 0.180 inches) related in diameter to passage 142 (e.g., 0.360 inches).

There are formed in plate 143 a primary resonant cavity 146 and auxiliary resonant cavities 147, 148, 149, 150, 151, 152, and 153. Primary cavity 146 is coupled to auxiliary cavity 153 by a slot 154. One end of primary cavity 146 and auxiliary cavity 153, and auxiliary cavities 147, 148, and 149 are distributed at 90° intervals about the periphery of hole 155. Similarly, the other end of primary cavity 146 and auxiliary cavity 153, and auxiliary cavities 150, 151, and 152 are distributed at 90° intervals about the periphery of hole 156. Primary cavity 146, auxiliary cavity 153, and slot 154 all have an identical height Z_1 (e.g., $Z_1 = 0.180$ inches). Primary cavity 146 has a depth X_1 (e.g., $X_1 = 0.180$ inches) and a non-significant length that extends completely across the space between holes 155 and 156. Slot 154 has a width Y_2 and a depth X_2 ($Y_2, X_2 = 0.090$ inches). Auxiliary cavity 153 has a depth X_3 (e.g., $X_3 = 0.090$ inches) and a non-significant length that extends completely across the space between holes 155 and 156. Auxiliary cavities 147, 148, 149, 150, 151, and 152 all preferably have identical dimensions, namely, a height Z_4 , a width Y_4 , and a depth X_4 (e.g., $Z_4, Y_4, X_4 = 0.180$ inches). The dimensions $X_1, Z_1, X_2, Y_2, X_3, X_4, Y_4$, and Z_4 , and the diameter of passage 142 which are related to the wavelength of the shock waves from unit 139 and the wavelength of the pressure pulses characteristic of conduit 117, are all significant. For ease of fabrication, the back wall of cavities 147 through 152 (i.e., the wall opposite the open side of the cavities) could be rounded somewhat. Thus, these cavities may be formed by machining. Instead of being cubicle, these auxiliary cavities could be non-cubicle hexahedral. In summary, all the dimensions of the resonant cavities and conduits leading thereto are matched, so to speak, to the wavelength of the pressure pulses.

For the linear cross-sectional dimensions of conduit 117, a rather large value relative to the wavelength of the pressure pulses produced by generator 119 is selected in order to provide a large rate of fluid flow. As indicated above, this results in characteristic pressure pulses having a rather large wavelength. On the other hand, shock wave generator 119 produces pressure pulses with a small wavelength. The large and small wavelengths are both dimensionally related to each

other and the dimensions of the resonant cavities. When the large wavelength energy produced by conduit 117 and small wavelength energy produced by shock wave generator 119 combine in cavity 118, in addition to the resonant process, an energy mixing process apparently takes place. This mixing action increases the energizing capability of the coherent sonic wave energy produced and apparently decreases the wavelength of the predominant energy component wavelengths of the pressure waves produced. At any rate, a fluid flowing at a high flow rate is effectively energized by this embodiment.

As illustrated by the preceding description of the various embodiments and arrangements of the invention, there is a relationship among the significant dimensions of the arrangements, e.g., distance and cross section, and the wavelength or wavelength components of the pressure waves. Broadly, the rule to follow is that the significant dimensions and the wavelength of the pressure waves are multiples of a common divisor. For example, with a significant dimension of 0.270 inches and pressure waves having a wavelength of 0.180 inches, the common divisor is 0.090 inches, the cross-sectional side dimension is a multiple of three, and the pressure wave wavelength is a multiple of two. More specifically, the significant dimensions and the wavelength of the pressure waves are preferably multiply related. The multiple is as close to one as practical. If it is practical to make the multiple one, the significant dimensions and the pressure wave wavelength are equal. In practice, the mixing action is preserved until the significant dimensions deviate from the wavelength of the pressure waves by one-quarter wavelength and some of the significant dimensions are only preferable; the mixing action takes place to some extent without meeting the relationship with regard to such preferable significant dimensions. As a design guide, when the actual dimensional relationships for pressure wave wavelength and the significant dimensions are met to within ± 10 percent of the prescribed nominal values, the described results are in fact achieved. Beyond a ± 10 percent deviation, the results drop off but are still usable.

The described embodiments of the invention are only considered to be preferred and illustrative of the inventive concept; the scope of the invention is not to be restricted to such embodiments. Various and numerous other arrangements may be devised by one skilled in the art without departing from the spirit and scope of this invention. For example, the different types of pressure wave generators and mixers in the various embodiments could be interchanged. In fact, a number of the devices disclosed in the drawings illustrate the principles of more than one embodiment. The device of FIG. 3 involves the principles of the fourth embodiment as well as the first embodiment because of the resonant dimensioning of manifold 29. The device of FIG. 4 coupled to generator 25 involves the principles of the first embodiment through the action of the holes in cell 35 and the principles of the second embodiment through the interaction of cell 35 with cells 36 and 37. Generator 61 in FIG. 5 involves the principles of the third embodiment by virtue of the convergence of pressure waves from channels 50 through 53 upon the fluid stream flowing through passage 40 in the direction of arrow 42. The device of FIG. 6 involves the principles of the first embodiment, in addition to the second em-

bodiment, because of the action of the holes in cell 77.

What is claimed is:

1. A pressure wave mixing system comprising:
a first pressure wave generator with an outlet from which pressure waves emanate, the pressure waves from the first generator having a first wavelength;
- a second pressure wave generator with an outlet from which pressure waves emanate, the pressure waves from the second generator having a second wavelength related to the first wavelength; and
means for supporting the first and second generators so the pressure waves emanating from them combine at a point spaced from the outlet of each of the generators a distance related to the wavelength of the pressure waves from such generator.
2. The system of claim 1, in which the first and second generators each generate coherent sonic wave energy.
3. The system of claim 1, in which the first and second generators each generate coherent shock wave energy.
4. The system of claim 1, in which the first generator generates coherent shock wave energy and the second generator generates pressure pulses characteristic of a simple orifice.
5. A pressure wave mixing system comprising:
first means for generating pressure waves having a given wavelength;
means for directing the pressure waves generated by the first generating means along a first axis;
second means for generating pressure waves having a wavelength related to the given wavelength; and
means for directing the pressure waves generated by the second generating means along a second axis that intersects the first axis at a point of intersection.
6. The system of claim 5, in which the distance along the first axis from the first generating means to the point of intersection and the distance along the second axis from the second generating means to the point of intersection are related to the given wavelength.
7. The system of claim 6, in which the distances and the given wavelength are multiples of a common divisor.
8. The system of claim 6, in which the distances are multiply related to the given wavelength.
9. The system of claim 5, in which each generating means comprises a supersonic nozzle and means for producing a sufficient pressure drop across the nozzle to cause supersonic fluid flow along the corresponding axis in the direction of the point of intersection.
10. The system of claim 5, in which each generating means comprises a shock wave generating cell having an inlet to which a gas under pressure is applied and an outlet aligned with the corresponding axis to radiate shock waves along such axis.
11. The system of claim 5, in which the first and second axes are substantially perpendicular to each other.
12. A pressure wave mixing system comprising:
a plurality of sources of pressure waves having related wavelengths; and
means for mixing the pressure waves from the plurality of sources to enhance the energizing capability

and/or the propagating range of the resultant pressure waves.

13. A pressure wave mixing system comprising:
a first source of pressure waves having a first wavelength;
a second source of pressure waves having a second wavelength related to the first wavelength;
a resonant cavity having a cross-sectional dimension related to the first and second wavelengths; and
means for coupling the first and second sources to the cavity.
14. The system of claim 13, in which the first wavelength is a large multiple of the second wavelength.
15. The system of claim 14, in which the cavity has a square cross section with a side dimension related to the first and second wavelengths.
16. The system of claim 15, in which the first source is a conduit having a cross-sectional dimension related to the first and second wavelengths, the conduit producing characteristic pressure pulses at a wavelength that is a multiple of the wavelength of the pressure waves from the second source, and the coupling means comprises a connection of the conduit to the cavity and a connection of the second source to the conduit.
17. Pressure wave mixing apparatus comprising:
means for producing a stream of fluid;
means for establishing pressure waves in the stream; and
means for forming a plurality of passages having cross-sectional dimensions related to the wavelength of the pressure waves, the passages having inlets in communication with the pressure waves and outlets in communication with each other for mixing the pressure waves passing through the passages.
18. The apparatus of claim 17, in which the passage forming means comprises a shock wave generating cell having a number of boundary layer forming holes constituting the passages.
19. The apparatus of claim 17, in which the passage forming means comprises a plate that is thin relative to the wavelength of the pressure waves, the plate having perforations with a diameter related to the wavelength of the pressure pulses and a spacing from each other related to the wavelength of the pressure waves.
20. The apparatus of claim 17, in which the passage forming means comprises a housing having a plurality of parallel tubes, the tubes having a diameter, a length, and a spacing from each other related to the wavelength of the pressure waves.
21. The apparatus of claim 20, in which the housing has a first manifold communicating with one end of the tubes and a second manifold communicating with the other end of the tubes, the first and second manifolds having a depth related to the wavelength of the pressure waves to form resonant cavities.
22. The apparatus of claim 17, in which the pressure waves are coherent sonic waves.
23. Pressure wave mixing apparatus comprising:
first means responsive to flowing fluid for generating in the fluid coherent shock waves having a first wavelength;
second means responsive to flowing fluid for generating in the fluid coherent shock waves having a second wavelength, the first and second wavelengths being related; and

means for orienting the first and second shock wave generating means so the shock waves therefrom converge at a point.

24. The apparatus of claim 23, in which the first and second wavelengths are multiple related.

25. The apparatus of claim 23, in which the first and second wavelengths are multiples of a common divisor.

26. The apparatus of claim 23, in which the first and second wavelengths are equal.

27. The apparatus of claim 23, in which the first and second shock wave generating means are oriented so the shock waves therefrom converge at right angles to each other.

28. The apparatus of claim 23, in which the distance from each of the shock wave generating means to the point of convergence is related to the first and second wavelengths.

29. The apparatus of claim 23, in which the first and second shock wave generating means each comprise a cylindrical nozzle body having a downstream end and an upstream end, there being a pressure drop between the upstream end and the downstream end, the nozzle body being open at its downstream end, bounded along its length by a sidewall and bounded at its upstream end by an end wall having a large center hole, a plurality of smaller equally spaced peripheral holes disposed about the center hole in the end wall in oppositely arranged pairs, a plurality of oppositely disposed pairs of throat plane stabilizing holes lying in a common plane in the sidewall near the downstream end of the nozzle body, and a cylindrical cell cover enclosing the nozzle body to form an annular region surrounding the cylindrical side wall of the nozzle body, the cell cover completely enclosing the nozzle body except for the open downstream end of the nozzle body and an opening at its upstream end that communicates with the holes in the nozzle body, the holes of the nozzle body all having dimensionally related diameters.

30. Pressure wave mixing apparatus comprising:
means responsive to flowing fluid for producing in the fluid coherent shock waves having a first wavelength;

means responsive to flowing fluid for producing in the fluid pressure pulses having a second wavelength, the second wavelength being a large multiple of the first wavelength; and

means for orienting the shock wave generating means and the pressure wave generating means so the waves therefrom converge at a point.

31. The apparatus of claim 30, in which the means for generating pressure pulses comprises a simple orifice having a diameter related to the first wavelength and means for inducing fluid flow through the orifice toward the point of convergence.

32. The apparatus of claim 31, in which the shock wave generating means comprises a cylindrical nozzle body having a downstream end and an upstream end, there being a pressure drop between the upstream end and the downstream end, the nozzle body being open at its downstream end, bounded along its length by a sidewall and bounded at its upstream end by an end wall having a large center hole, a plurality of smaller equally spaced peripheral holes disposed about the center hole in the end wall in oppositely arranged pairs, a plurality of oppositely disposed pairs of throat plane stabilizing holes lying in a common plane in the side-

wall near the downstream end of the nozzle body, and a cylindrical cell cover enclosing the nozzle body to form an annular region surrounding the cylindrical side wall of the nozzle body, the cell cover completely enclosing the nozzle body except for the open downstream end of the nozzle body and an opening at its upstream end that communicates with the holes in the nozzle body, the holes of the nozzle body all having dimensionally related diameters.

33. The apparatus of claim 31, comprising one or more additional means responsive to flowing fluid for generating in the fluid shock waves having a first wavelength, the additional shock wave generating means being oriented so the shock waves converge at the point.

34. The apparatus of claim 30, in which the distance between the shock wave generating means and the point and the distance between the pressure pulse generating means and the point are related to the first and second wavelengths.

35. A method of enhancing the energizing capability and/or propagating range of pressure waves, the method comprising the steps of:

generating pressure waves having a first wavelength in a first fluid stream;

generating pressure waves having a second wavelength in a second fluid stream, the first and second wavelengths being related; and

means for directing the first and second fluid streams to converge at a point so as to mix the pressure waves therein.

36. A method of enhancing the energizing capability and/or propagating range of pressure waves, the method comprising the steps of:

generating pressure waves having a given wavelength; and

coupling the pressure waves to the inlets of a plurality of passages each having a cross-sectional dimension related to the given wavelength and an outlet in communication with the outlets of the other passages.

37. A method of energizing a fluid stream comprising:

passing the fluid stream through a large orifice to produce in the fluid stream pressure pulses characteristic of the orifice, the pressure pulses having a given wavelength; and

directing into the stream downstream of the orifice coherent shock waves having a wavelength related to the given wavelength.

38. A method of generating sonic wave energy having a high energy capability and a short wavelength, the method comprising the steps of:

producing pressure pulses having a large wavelength in a fluid with a large rate of flow;

producing pressure pulses having a small wavelength, the large wavelength and the small wavelength being dimensionally related; and

combining and resonating the pressure pulses having the large wavelength and the pressure pulses having the small wavelength to generate sonic waves.

39. The method of claim 38, in which the combination of pressure pulses is simultaneously resonated in a first dimension between a first pair of parallel reflective surfaces and in a second dimension perpendicular to the first dimension between a second pair of parallel reflective surfaces to convert the pressure pulses into sonic wave energy, the first and second dimensions being related.

40. The method of claim 38, in which the pressure pulses are combined and resonated in separate steps.

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