

[54] **APPARATUS FOR PRODUCING A FUEL-AIR MIXTURE BY SONIC ENERGY**

[75] Inventor: Eric C. Cottell, Bayville Long, N.Y.

[73] Assignee: Resources Research & Development Corporation, El Paso, Colo.

[22] Filed: July 19, 1971

[21] Appl. No.: 163,603

**Related U.S. Application Data**

[63] Continuation-in-part of Ser. No. 109,109, Jan. 25, 1971, abandoned.

[52] U.S. Cl. .... 261/1, 261/50 R, 261/34 A, 261/69 R, 261/DIG. 48, 239/102 E

[51] Int. Cl. .... F02m 27/08

[58] Field of Search..... 261/1, DIG. 48, 34 A, 261/69 R, 50 R; 239/102

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Primary Examiner—Tim R. Miles

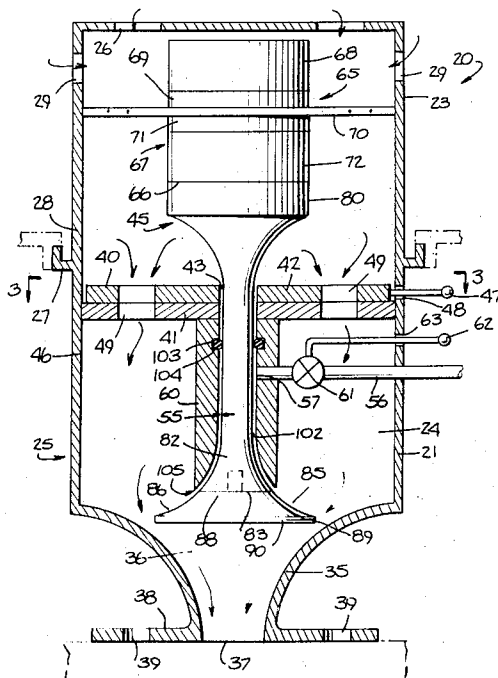
Attorney—Kenyon & Kenyon Reilly Carr & Chapin

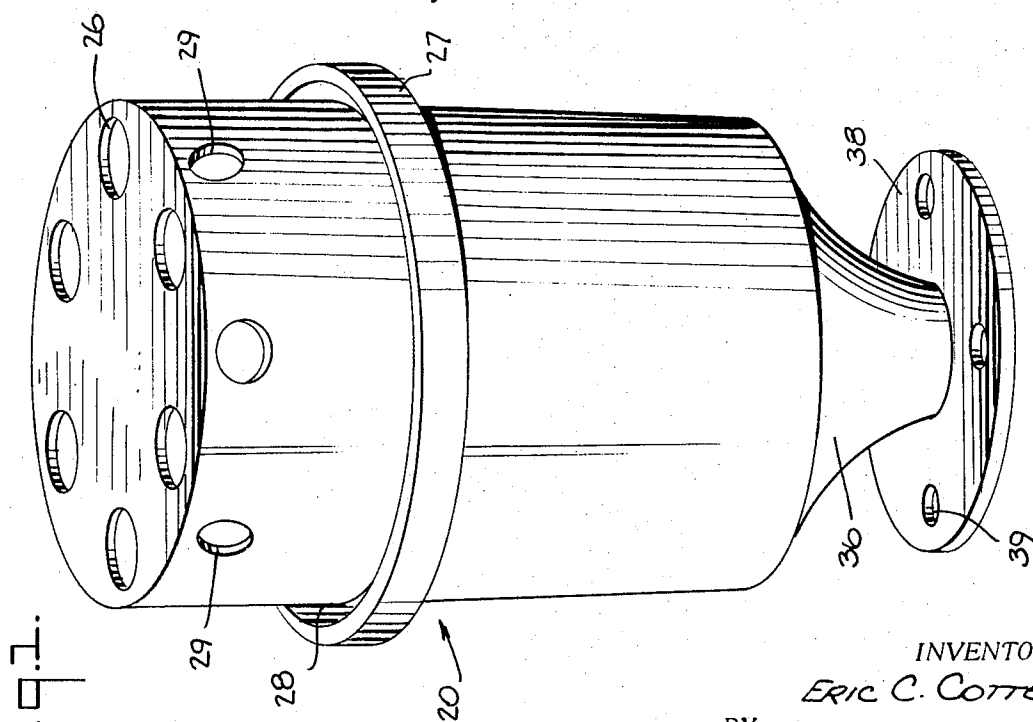
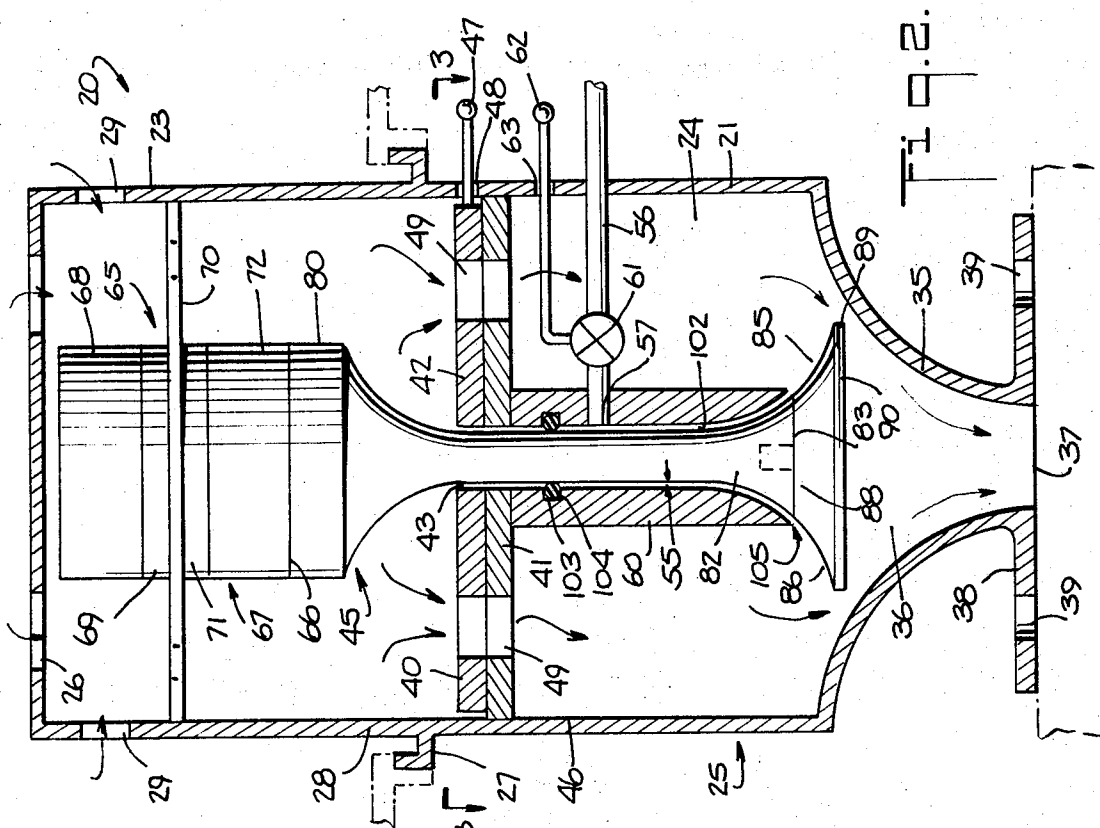
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**ABSTRACT**

An apparatus for supplying positively controlled amounts of an atomized and vaporized liquid fuel and air for combustion in an internal combustion engine, said apparatus comprising an energizable sonic probe, having a vibratory fuel atomizing surface at one end, and a conduit including a variable volume chamber and a main metering valve for distributing controlled amounts of fuel to a means for directing a thin film of fuel across the atomizing surface. The sonic vibrational energy of the sonic probe performs work on the film as it migrates across the atomizing surface, causing the fuel to atomize and vaporize. The atomizing surface is exposed to a flow of air moving towards the engine, and the atomized fuel is effectively mixed with the air to form a highly suitable fuel-air mixture for efficient combustion in the engine. A throttle valve controls the flow of air through the passageway. The main fuel metering valve and a means for varying the volume of the variable volume chamber positively control the amount of fuel supplied in relation to the amount of air supplied through the throttle valve. In a preferred embodiment, a bypass fuel valve responsive to intake manifold pressure prevents stalling at idle throttle setting and enriches the mixture under load conditions.

**11 Claims, 22 Drawing Figures**





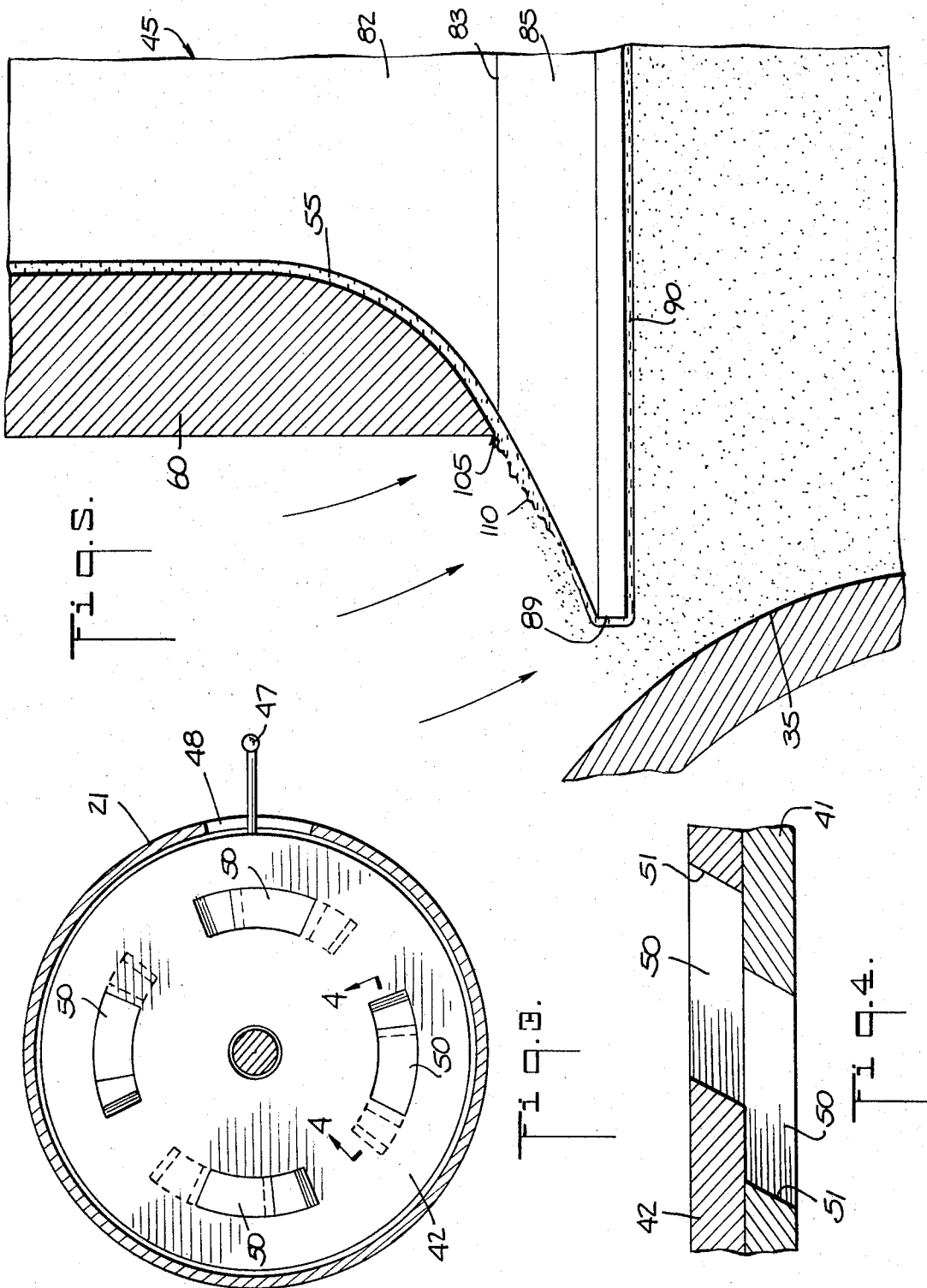
INVENTOR.

ERIC C. COTTELL

BY

*Tenyon & Tenyon, Reilly, Law & Chapin*

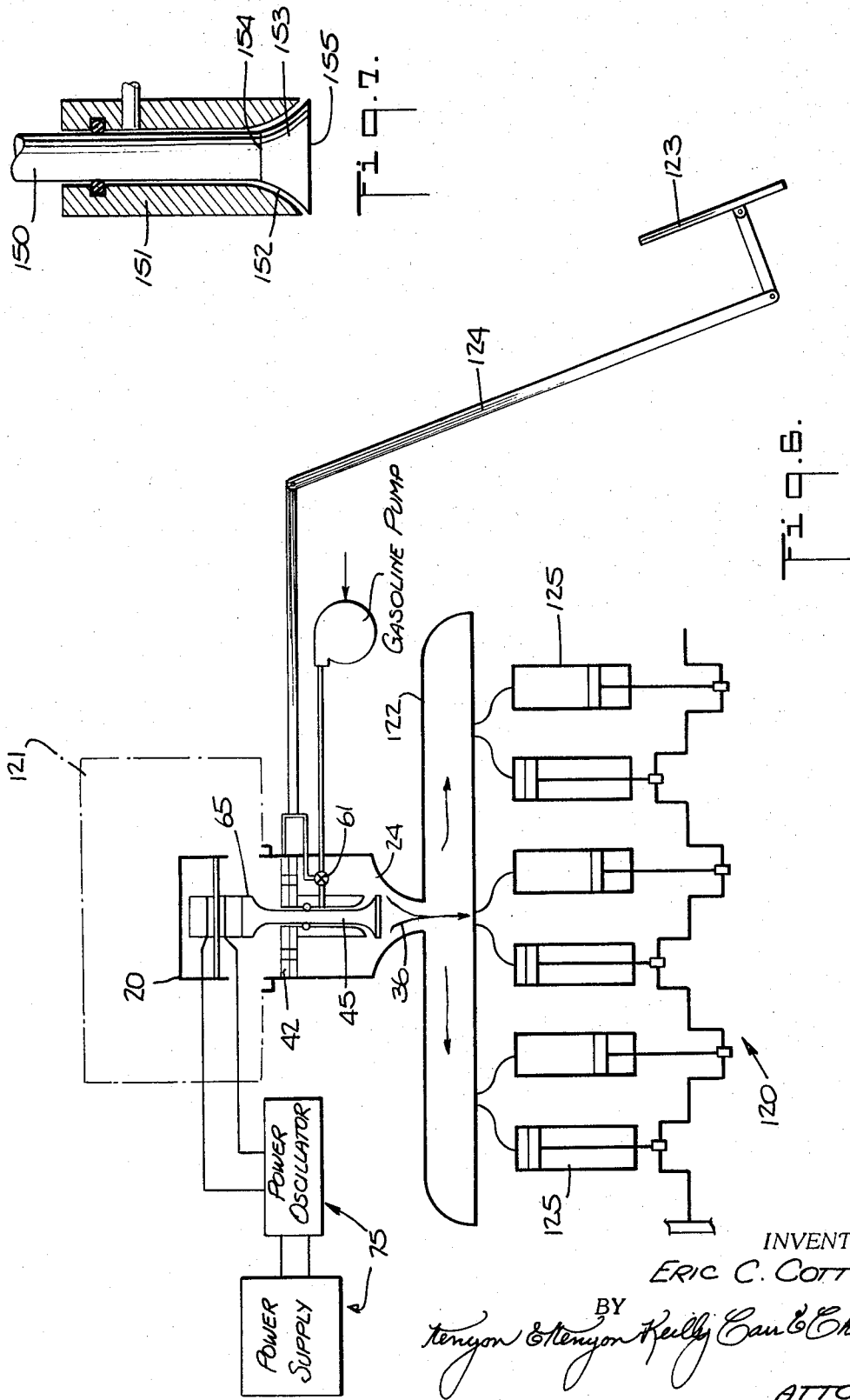
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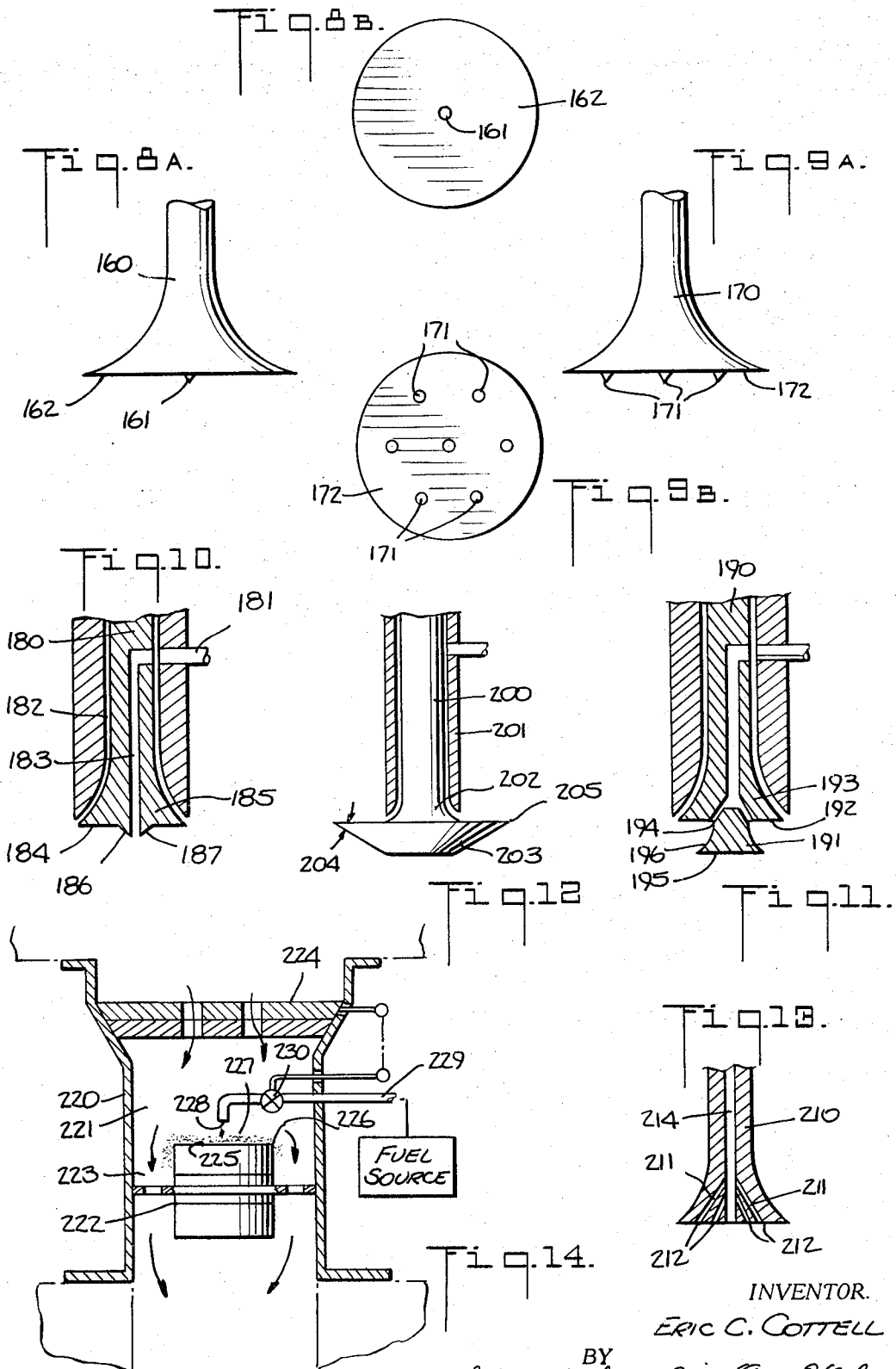


INVENTOR.

ERIC C. COTTELL

BY  
Kenyon & Kenyon Reilly Can & Chapin  
ATTORNEYS



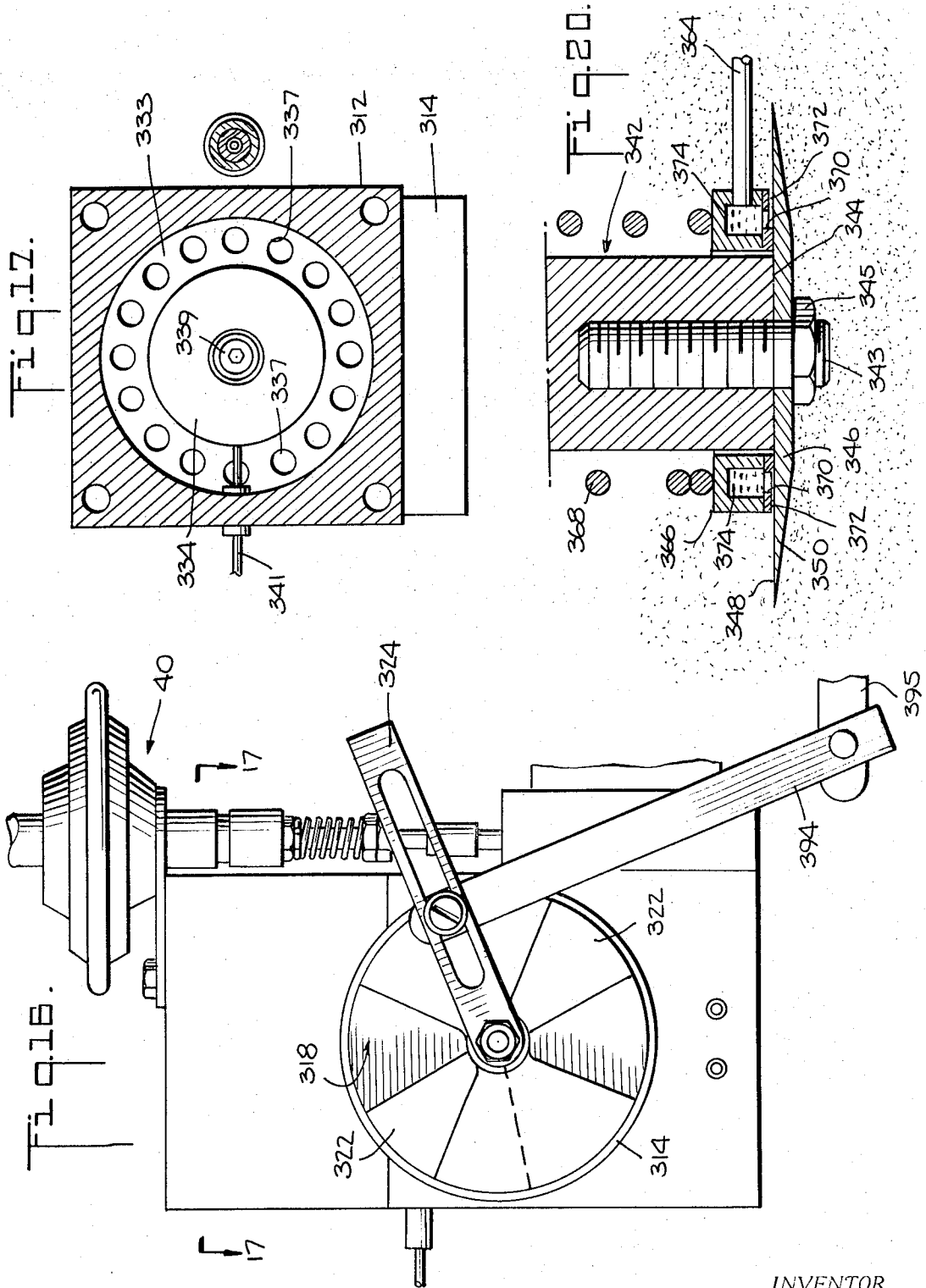


INVENTOR.

ERIC C. COTTELL

BY

*Kenyon Otterman Kelly Carr & Chapin*  
ATTORNEYS



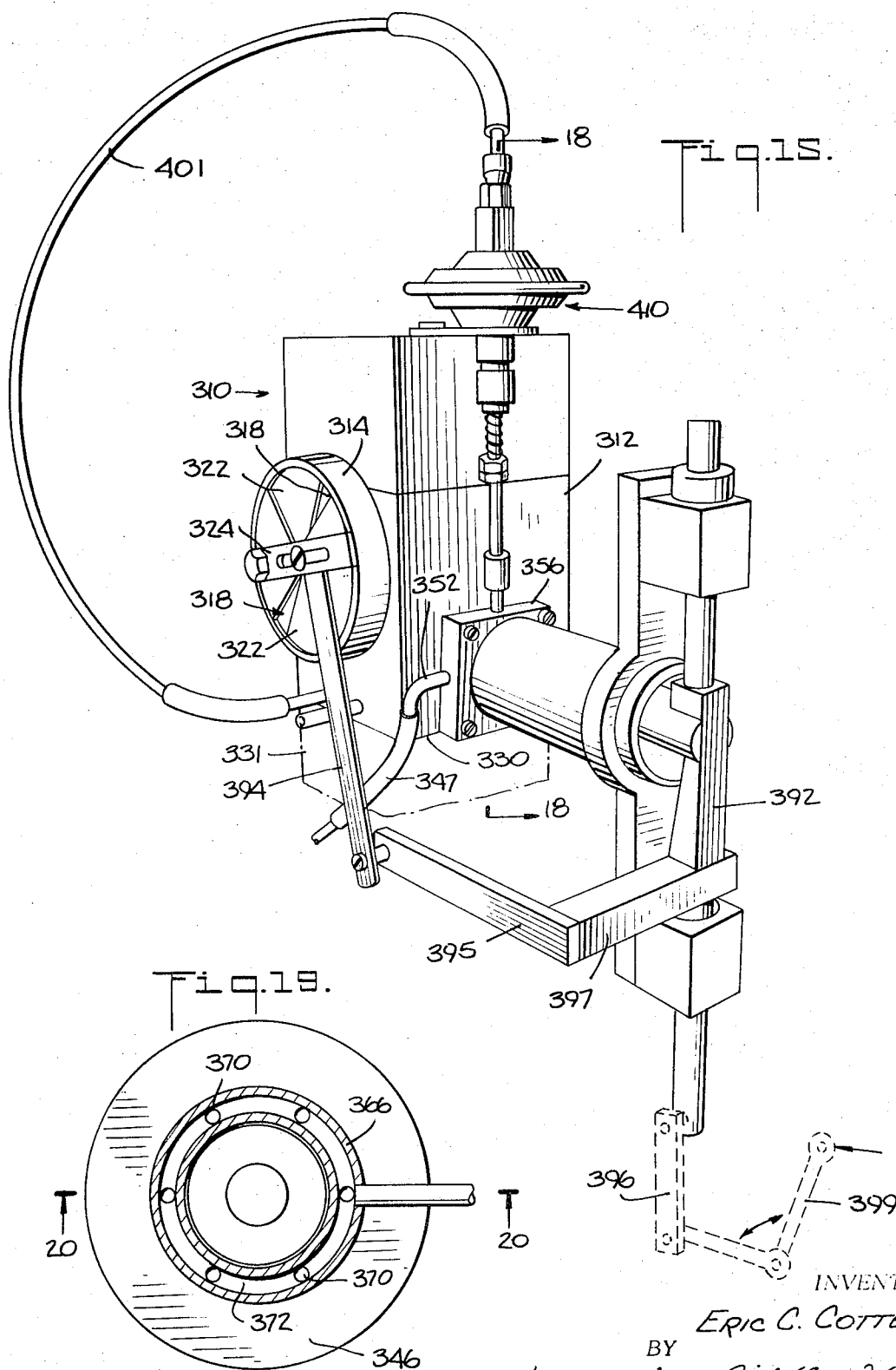
INVENTOR.

ERIC C. COTTELL

BY

*Kenyon & Kenyon Feilly Carr & Chapin*

ATTORNEYS

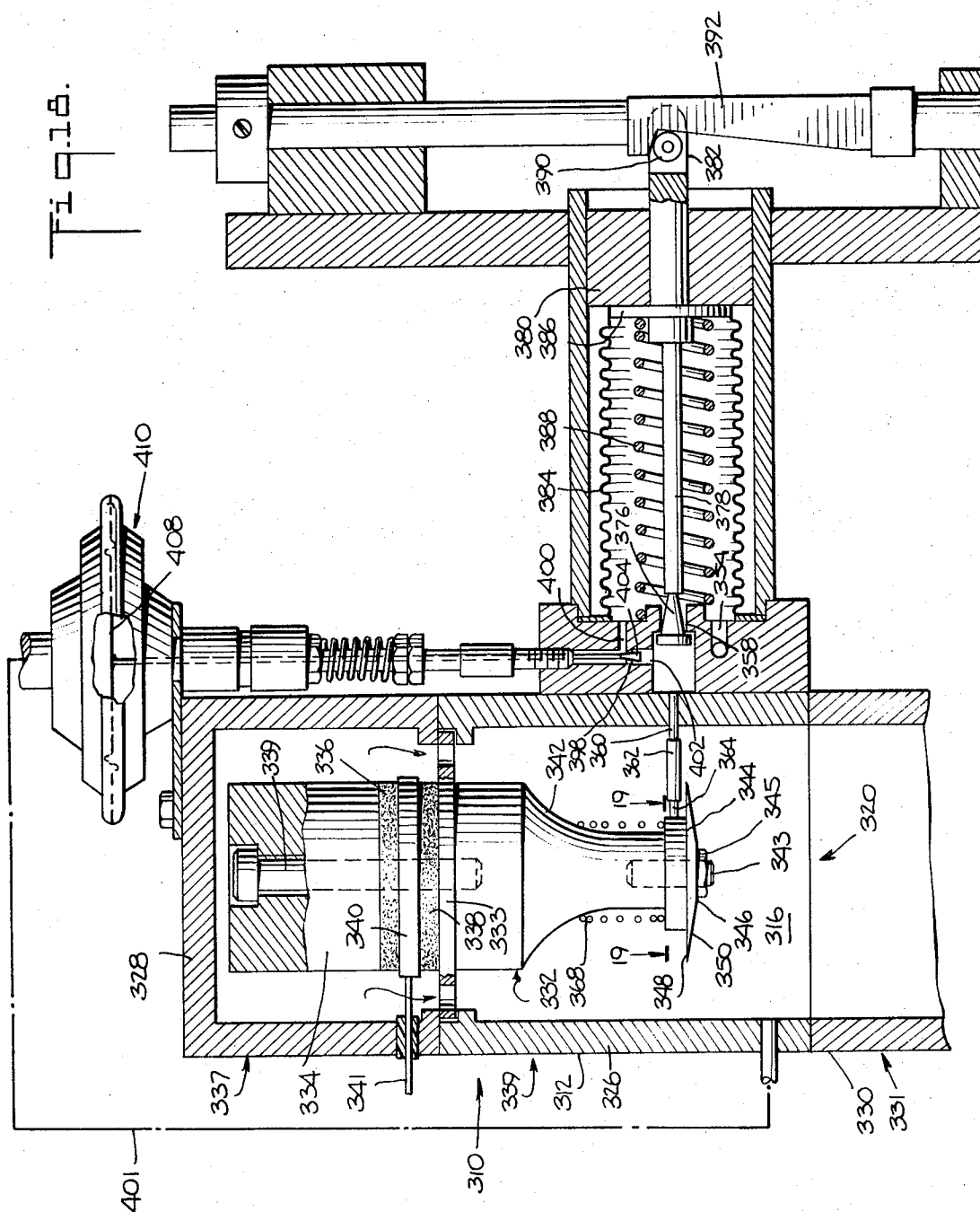


INVENTOR.  
 ERIC C. COTTELL  
 BY  
 Kenyon & Kenyon Reilly Carr & Chapin  
 ATTORNEYS

PATENTED SEP 4 1973

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SHEET 7 OF 7



INVENTOR.

ERIC C. COTTELL

BY

Kenyon & Kenyon Reilly Carr & Chapin  
ATTORNEY

ATTORNEY

## APPARATUS FOR PRODUCING A FUEL-AIR MIXTURE BY SONIC ENERGY

This is a continuation-in-part of my copending application Ser. No. 109,109 filed Jan. 25, 1971 now abandoned.

### BACKGROUND OF THE INVENTION

This invention relates generally to an apparatus for mixing a liquid hydrocarbon-containing fuel, such as gasoline, kerosene, diesel fuel, or jet fuel, with air to form a fuel-air mixture suitable for combustion in an internal combustion engine. More particularly, this invention relates to an apparatus for atomizing and vaporizing a positively controlled flow of fuel by means of sonic vibrational energy performing work on the fuel to atomize and vaporize it, thereby enhancing the mixing of the fuel with air flowing past the vibrational apparatus to form the fuel-air mixture.

Devices for supplying a fuel-air mixture to internal combustion engines must satisfy several requirements. First, the fuel must be as finely atomized and as thoroughly mixed with the air as possible to obtain the most complete combustion. Secondly, both the rates of flow of fuel and air and their ratio must be controllable over the full range of engine speeds and loads. At high speeds on engine requires more air and fuel than at low speeds; at high loads it usually requires a higher proportion of fuel to air than at no load.

Thirdly, the mixture should be temporarily enriched when accelerating and preferably leaned when decelerating. Finally, the fuel-air mixture must usually be enriched at idle to counteract the unfavorable effects of low charge densities and high exhaust gas contamination upon combustion.

Conventional automotive carburetors deliver atomized fuel from a spray nozzle in the throat of a venturi that forms part of an air flow passageway. Primary control of engine speed is by a throttle valve in the air passageway. The fuel supply is maintained at a constant level in a float chamber, and the flow rate of fuel adjusts automatically to the mass rate of air flow determined by the throttle setting, because of the inherent pressure-flow relation developed by the venturi. That is, venturi throat pressure decreases with increasing air flow, creating an increased pressure drop across the fuel spray nozzle and causing corresponding increase in fuel flow. The resulting fuel-air ratio is practically constant over a wide range of flow rates.

In order to provide fuel enrichment for acceleration, most carburetors have an accelerator pump, linked directly to the throttle valve control, which injects additional fuel through a separate spray nozzle as the throttle valve is opened. Additional fuel requirements at idle are usually met by a separate idle jet fed by a bypass from the line to the main fuel spray nozzle and with its outlet positioned in the high suction region near the edge of the throttle valve.

A still further refinement in some carburetors is to provide the metering orifice to the main fuel spray nozzle with a pressure-actuated needle valve responsive to the intake manifold pressure. For a given throttle valve setting, intake manifold absolute pressure increases as engine speed decreases under load. The needle valve is connected so as to open with increasing intake manifold pressure to supply additional fuel through the main

spray nozzle and enrich the mixture as the load increases.

Although the above and other refinements contribute to smooth and responsive performance under a wide range of operating conditions, the heart of the conventional automotive carburetor is the venturi-controlled main fuel spray nozzle, with its attendant advantages and disadvantages.

A conventional carburetor has a major shortcoming in providing a fuel-air mixture. A conventional carburetor does not sufficiently atomize the liquid fuel to allow for a complete and uniform distribution of the fuel within the fuel-air mixture. As a result, some of the fuel separates or condenses out of the fuel-air mixture onto the walls of the manifold while it is being transferred to the combustion chamber of the internal combustion engine. In addition, the throttle valve is normally placed downstream of the atomizing section of a carburetor to isolate the venturi from the effects of varying intake manifold pressure. The throat pressure (and resulting fuel metering action) thus is a function only of the mass rate of air flow through the carburetor. This downstream throttle location has a countervailing disadvantage, however. The adiabatic expansion of the fuel and air mixture as it flows through the throttle valve cools the mixture and condenses some of the vaporized fuel into a liquid film on the throttle structure itself as well as on the walls of the intake manifold. Such fuel condensation reduces the homogeneity of the fuel-air mixture with resulting decreased burning efficiency and increased amounts of undesirable combustion products in the engine exhaust. When the insufficiently mixed fuel-air mixture is ignited in a cylinder, it does not burn completely and efficiently but instead leaves unburned combustion products and undesirable exhaust products in the exhaust gas.

A second shortcoming of a conventional engine equipped with a carburetor occurs during periods of high engine deceleration. The high vacuum in the intake manifold of the engine during deceleration causes excess fuel to be provided to the engine which further increases the amount of undesirable exhaust products in the exhaust gas.

A third shortcoming of a conventional engine equipped with a carburetor occurs during periods of starting up or warming up the engine. During this period the fuel-air ratio is maintained at a high level by choking and, consequently, the amount of undesirable exhaust products such as unburned hydrocarbons is very high.

These deficiencies produce several undesirable consequences. In the first place, the inefficient burning of the fuel-air mixture provided by the conventional carburetor results in greater specific fuel consumption by the internal combustion engine than would be required with more complete atomization of the fuel by a carburetor. Secondly, and more importantly from an ecological viewpoint, oxygen which has not been combined with carbon in the combustion process can combine with nitrogen and carbon atoms also present in the combustion chamber to form undesirable products in the exhaust gas such as carbon monoxide and nitrous oxides. In addition, fuel which has not been combined with oxygen can appear as unburned hydrocarbons in the exhaust gas.

There have been proposals in the past to use sonic energy or vibrations to achieve finer fuel atomization

and thus an improved fuel-air mixture for internal combustion engines.

For example, U.S. Pat. No. 2,908,443 issued Oct. 13, 1959 to F. Fruengel discloses an automotive fuel-air mixing device that includes a flat, upward-facing vibratory plate mounted in the bottom of a closed chamber leading to an engine intake manifold. A fuel inlet tube above the vibratory plate dispenses drops of fuel upon the plate where they are atomized. The resulting fuel vapor then passes out of the container under the influence of the intake suction in the manifold to mix with the air passing through the manifold to the engine. A valve in the fuel inlet tube controls the rate of fuel delivery to the vibratory plate. There is no positive means for controlling the amount of fuel that leaves the chamber to mix with the air flowing to the engine. Further, the Fruengel device would appear to permit recondensation of the fuel in the chamber prior to mixing with the air flowing to the engine, thus negating its purpose.

D. A. Trayser et al., in a report entitled "A Study of the Influence of Fuel Atomization, Vaporization and Mixing Processes on Pollutant Emissions from Motor-Vehicle Powerplants" published by Battelle Memorial Institute, Columbus, Ohio on Apr. 30, 1969, discuss the influence of conventional carburetor design upon fuel condensation with resulting nonuniform fuel-air mixtures supplied to the cylinders of an engine.

One of the suggestions of the Trayser et al., study is to replace the main atomizing jet in a conventional carburetor with a piezoelectric ultrasonic atomizer. The proposed ultrasonic atomizer has a cylindrical aluminum horn facing downstream in a constricted region of an air passageway. A piezoelectric disk mounted on the upstream end causes the downstream end of the horn to vibrate in a radial mode. Fuel flows onto the cylindrical outer surface of the horn through a ring of small orifices spaced around the upper end of the atomizer and cascades down towards the radially vibrating lower edge where it is atomized and mixes with the air flowing through the constricted passageway.

Fuel rate in the Trayser et al. proposed device is controlled by pressure drop generated by the amount of air flowing through the constricted region, just as in a conventional carburetor. The air, in turn, is controlled by conventional throttle plates below the atomizer, thus retaining the inherent drawback of a fuel condensation surface located downstream of the atomizing device. As an alternative, however, Trayser et al. suggest eliminating the throttle plates and controlling air flow by axial movement of the atomizer to vary the flow area through the constricted region. A separate fuel valve adjusted by the linkage controlling the axial position of the atomizer would be needed to provide the desired fuel-air ratio over the load range. For this alternative embodiment, separate fuel orifices and air holes would be required for idle operation when the atomizer body would completely close the constricted passageway.

The devices proposed by Trayser et al. are based on a study of the prior art and, admittedly, might not prove to be practical upon further development. In particular, the delivery of fuel from jets spaced around the atomizing surface could result in forming a substantial proportion of relatively large droplets which bounce off the upper portion of the cylindrical horn before absorbing significant vibrational energy.

## SUMMARY OF THE INVENTION

The apparatus of the present invention provides a means for effectively mixing positively controlled amounts of a liquid hydrocarbon containing fuel such as gasoline, kerosene, diesel fuel or jet fuel with air to form a fuel-air mixture highly suitable for efficient combustion in an internal combustion engine. The apparatus receives the hydrocarbon fuel in its liquid state and, by means of sonic vibrational energy, performs work on the fuel, transforming it to a highly atomized state. The fuel can thereafter be effectively mixed with air to form a more uniform fuel-air mixture. The highly atomized state of the fuel promotes vaporization of volatile hydrocarbon fuels, thereby further enhancing the mixing of the fuel with the air.

According to one preferred embodiment, the apparatus functions in place of a carburetor and choke to provide a fuel-air mixture for combustion in an internal combustion engine. The apparatus comprises a housing having an air flow control at the top for admitting a controlled flow of air into the housing and an outlet at the bottom for discharging a fuel-air mixture formed within the housing either directly into the cylinders or into the intake manifold of the engine. An energizable sonic transducer mounted within the housing transmits sonic vibrational energy to a sonic probe having fuel atomizing surfaces at the lower end thereof. Mounting the transducer within the housing provides the additional benefit of cooling the transducer by the air flowing through the housing to the engine. A thin, unconfined film of fuel is directed onto the atomizing surfaces from an annular fuel conduit within the housing. The sonic vibrational energy of the sonic probe performs work on the film as it moves along the atomizing surface, thereby causing the fuel to atomize and vaporize. The atomizing surface is exposed to the air flow passing through the apparatus, and the atomized fuel emitted from the surface effectively mixes with the air to form a highly suitable fuel-air mixture for efficient combustion in the engine.

The term "sonic," as used herein, is not intended to restrict the vibrational frequencies of the apparatus to the audible range, but is used to conveniently describe both audible frequencies (i.e., below 20 kHz) and ultrasonic frequencies (i.e., above 20 kHz). Further, the term "sonic probe," as used herein, is intended to be a generic term as applied in the field of sonics and, where not specified otherwise, a "sonic probe" includes the portion of the probe conveniently referred to below as a "sonic tip."

The apparatus of the present invention, as discussed above and as will be described more fully hereinafter, can replace the conventional carburetor or other means for providing the fuel-air mixture to internal combustion engines. For example, in an automobile, no modification of the existing engine would be required. The apparatus of the invention would be mounted between the air filter and the intake manifold of the engine in place of the existing conventional carburetor. The only additional equipment required would be a battery operated power oscillator to provide the sonic vibrational energy to the transducer of the apparatus. Some modifications to the existing linkage extending from the accelerator pedal would be required in connecting it to the apparatus for selecting the quantity of intake air and the amount of fuel to be supplied by the

apparatus. As will be discussed further, the apparatus promotes rapid starting of the automobile engine without need of a conventional choke.

The enhanced mixing by the apparatus of the hydrocarbon fuel with the air to form the fuel-air mixture improves engine efficiency and reduces the fuel consumption by the engine. Most importantly, the enhanced mixing reduces greatly the pollutants contained in the exhaust gas of the engine. As will be illustrated below, the apparatus of the present invention significantly reduced the pollutants contained in the exhaust gas of an automobile engine to amounts well below the maximum contents set by the recent federal legislation.

It is believed that the apparatus of the present invention accomplishes such a significant reduction in pollutants in exhaust gases of internal combustion engines for the following reasons. The enhanced mixing by the apparatus of the hydrocarbon fuel with the air produces a more uniform and homogenous fuel-air mixture. This allows for more complete combustion of the carbon atoms present in the fuel and more complete utilization of the oxygen atoms present in the air to form carbon dioxide, a relatively desirable combustion product when compared to carbon monoxide and nitrous oxides.

Further, the enhanced mixing results in a smoother, faster combustion of the fuel-air mixture and therefore the timing of the firing in an internal combustion engine cylinder may be delayed thereby reducing the interval of time that the ignited hydrocarbons are in cylinders. The maximum combustion gas temperature in the cylinders of a reciprocating internal combustion engine operating with the apparatus is reduced since the additive effect of the heat of compression of the fuel-air mixture and the heat of combustion is less than the additive effect present in a reciprocating internal combustion engine operating with a conventional carburetor. The correct timing of the ignition of the fuel-air mixture and the fewer oxygen atoms in the combustion gas significantly reduce the pollutants in the exhaust gas, particularly nitrous oxides.

The amount of nitrous oxides formed in the combustion gas of an internal combustion engine is particularly a function of the pressure and temperature of the combustion gas and the time available for their formation, as well as the number of nitrogen and oxygen atoms available to combine with one another. Nitrous oxides will not form in the combustion gas unless the temperature of the gas is in excess of approximately 3,000°F. Assuming other variables remain constant, the formation of nitrous oxides increases as the temperature of the gas increases. Further, assuming other variables remain constant, the amount of nitrous oxides formed increases with the residence time available for their formation. Therefore, it is believed that the apparatus reduces the amount of nitrous oxides formed in the combustion gas of internal combustion engines because the maximum temperature of the gas, while it may be in excess of 3,000°F. for many types and sizes of engines, is significantly below the maximum temperature of the combustion gas resulting from the use of a conventional carburetor and the timing of the ignition necessary therewith. Further, the delayed ignition time also reduces the time available for the formation of nitrous oxides in the combustion gas. Finally, the more complete combustion of the carbon atoms, significantly reduces the number of free oxygen atoms available to

combine with the nitrogen atoms to form nitrous oxides.

Finally, the flow of fuel onto the atomizing surfaces of the sonic probe of the apparatus of the invention is positively controlled by means of a valve. During periods of deceleration, as discussed above, unlike the analogous controls in a carburetor equipped engine, the valve reduces the flow of fuel to the amount required by the engine speed. Additionally, means can be provided, as provided with some fuel injection systems, to cause the valve to stop the flow of fuel during deceleration until the engine speed is reduced to a predetermined level at which time the appropriate amount of fuel can be again furnished to the engine. Thus, certain advantages of a fuel injection system are also obtainable with the apparatus of the present invention—the minimizing of excess amounts of fuel in the fuel-air mixture supplied to the engine during periods of deceleration—thereby further reducing undesirable exhaust products in the exhaust gas.

In a preferred version, the fuel valve is linked directly to the upstream air flow control or throttle. To provide enrichment when the throttle is advanced and leaning when the throttle is retarded, the fuel supply line to the fuel valve includes a variable volume chamber controlled by the valve actuator means.

When the throttle valve is opened, the actuator means increases flow area through the main fuel valve and simultaneously decreases the size of the variable volume chamber. The fuel displaced from the chamber by its reduction in volume serves to accelerate the engine to the speed determined by the new throttle setting, and the increased flow area through the main fuel valve provides the increased fuel flow needed to maintain this speed. Conversely, when the throttle valve setting is decreased, the actuator means correspondingly reduces the flow area through the main fuel valve and expands the variable volume chamber. This expansion produces a transient reduction in fuel flow, causing the engine to decelerate to the lower speed determined by the decreased throttle setting.

In a preferred embodiment of the invention, the main fuel valve is a reverse needle or a poppet-type valve with an elongated stem, and the variable volume chamber comprises a cylindrical accordian-type bellows coaxially surrounding the valve stem. One end of the bellows is fixed to the valve stem and the other end to the valve housing so that reciprocal axial movement of the stem both opens and shuts the valve and contracts and expands the chamber, respectively. An actuator means linked to the throttle valve adjusts the axial position of the fuel poppet valve stem in relation to the throttle valve setting and expands or contracts the bellows chamber when the throttle valve setting is changed.

As mentioned above, the invention includes a means for distributing the fuel in a thin film across a vibrating surface. Distributing the flow in a thin film produces improved atomization. In addition, the fuel distributing means necessarily has a restricted exit area which isolates the fuel supply line from the effects of the variable pressure environment downstream of the throttle valve.

Because the main fuel valve must handle a wide variation in flow rates, it is difficult to accurately adjust for the very small fuel flow at idle. Preferably, therefore, the main fuel valve shuts tight at idle, and fuel supply under this condition is provided through a vacuum-operated bypass valve. This bypass valve shuts when

there is high vacuum in the intake manifold, as during deceleration and normal idle. If the engine starts to stall, however, the intake manifold vacuum will drop sharply, causing the bypass valve to open and supplying more fuel to the vibratory atomizing surface.

The vacuum-operated bypass valve of the invention performs an additional fuel enrichment function when the intake manifold vacuum drops under load conditions at partial or full open throttle, thus eliminating the need in most cases for a separate fuel enrichment valve.

The invention thus makes possible improved atomization of fuel with positive control over the fuel-air mixture under all operating conditions of an automotive internal combustion engine by means of a relatively simple device requiring few adjustments.

Accordingly, it is an object of the invention to provide an apparatus for internal combustion engines which will reduce the pollutants, and particularly nitrous oxides, carbon monoxide and unburned hydrocarbons contained in the exhaust gas of an internal combustion engine.

Another object of the invention is to provide an apparatus which will provide a highly uniform mixture of a fluid hydrocarbon fuel and air for more complete and efficient combustion in an internal combustion engine.

Still another object of the invention is to provide the highly uniform fuel air-mixture by means of a surface energized with sonic vibrations which performs work on a thin film of fuel to transform it into a highly atomized and vaporized state prior to mixing the fuel with the air.

Still another object of the invention is to provide positively controlled amounts of fuel in relation to air for best operation with minimum production of pollutants for all conditions of internal combustion engine operation.

These and other objects, advantages and features of the invention will become more apparent from the following description, when read in conjunction with the accompanying drawings.

#### DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a perspective view of one preferred embodiment of the apparatus of the invention.

FIG. 2 shows a cutaway side elevation view of the apparatus of FIG. 1.

FIG. 3 shows a cross-sectional view of the apparatus shown in FIG. 2.

FIG. 4 shows a second cross-sectional view of the apparatus shown in FIG. 2.

FIG. 5 shows a close-up view of the sleeve and the sonic probe of the apparatus shown in FIG. 2.

FIG. 6 shows a schematic drawing of the apparatus, functioning as a carburetor for a conventional reciprocating internal combustion engine for an automobile.

FIG. 7 shows another embodiment of a sonic probe for the apparatus.

FIG. 8 (a) and (b) show still another embodiment of a sonic probe for the apparatus.

FIG. 9 (a) and (b) show still another embodiment of a sonic probe for the apparatus.

FIG. 10 shows still another embodiment of a sonic probe for the apparatus.

FIG. 11 shows still another embodiment of a sonic probe for the apparatus.

FIG. 12 shows still another embodiment of a sonic probe for the apparatus.

FIG. 13 shows still another embodiment of a sonic probe for the apparatus.

FIG. 14 shows a cutaway side elevation view of another embodiment of the apparatus of the invention.

FIG. 15 shows a perspective view of another preferred embodiment of the apparatus of the invention.

FIG. 16 shows a side view of the apparatus of FIG. 15.

FIG. 17 shows a partial section view along the line 17—17 of the apparatus FIG. 16.

FIG. 18 shows a partial section view along the line 18—18 of the apparatus of FIG. 15.

FIG. 19 shows a section view along the line 19—19 of the apparatus of FIG. 18.

FIG. 20 shows a section view along the line 20—20 of the apparatus of FIG. 19.

#### DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to the drawings one preferred embodiment of the apparatus for an internal combustion engine is illustrated in FIGS. 1—5. With particular reference to FIGS. 1—2, the apparatus 20 comprises a cylindrical housing 21 having an air-intake chamber 22 in the upper portion 23 and a mixing chamber 24 in the lower portion 25 of the housing 21. A flange 27, mounted to the outer wall 28 of the upper portion 23 of the housing permits attachment of a conventional air filter (shown in phantom) to completely surround the upper portion 23 of housing 21. Air intake ports 26 and 29 through the housing 21 are evenly disposed around the perimeter of the upper portion 23 of the housing 21 to admit air into the intake chamber 22. The inner walls 35 of the lower portion 25 of the housing 21 preferably form a converging nozzle section 36. Preferably, the inner walls 35 of the nozzle section 36 follow an exponential path from the mixing chamber 24 to an outlet 37 at the bottom of the housing 21. An annular flange 38 at the bottom of the housing 21 has several holes 39 passing therethrough to permit the apparatus 20 to be attached to an intake manifold (shown in phantom) of an internal combustion engine in place of a conventional carburetor.

The quantity of air passing into the apparatus 20 through intake ports 26 and 29 and into the intake manifold is controlled by an air flow control 40 mounted between the intake chamber 22 and the mixing chamber 24. The air flow control 40 comprises a fixed lower plate 41 and a rotatable upper plate 42. A hole 43 through the center of each of the plates 41 and 42 provides a passage for a sonic probe 45. There is clearance between the plates 41 and 42 and the sonic probe 45. The lower plate 41 is mounted to the wall 46 of the housing 21. The upper plate 42 is pivotally mounted above the lower plate 41 to rotate about the longitudinal axis of the sonic probe 45. Connected to the upper plate 42 is an arm 47 which extends radially outward from the plate 42 and through a slot 48 in the housing 21. The arm 47 is responsive to movement of a linkage means from the accelerator pedal (not shown) and controls the rotational position of the upper plate 42 with respect to the lower plate 41.

Referring to FIGS. 2—4, each of the plates 41 and 42 has mating air flow control ports 49 extending through the plate and disposed symmetrically about the center of the plate. The arm 47 rotates the upper plate 42 between a first position and a second position. In the first

position, the control ports 49 in the upper plate 42 are offset from the corresponding control ports 49 in the lower plate 41 so that little or no air can pass through the air flow control 40. In the second position, the control ports 49 in the upper plate 42 are aligned with the corresponding control ports 49 in the lower plate 41 so that a sufficient amount of air to sustain ignition and combustion in the engine at high speeds and loads can flow into the mixing chamber 24. As the upper plate 42 rotates between the first position and the second position, the amount of air that can flow through the air flow control 40 increases from zero to the maximum amount.

The shape of the control ports 49 is preferably chosen to encourage effective mixing of the air with the fuel and to provide close control of the volume of air flow at each setting. In FIGS. 3-4, the control ports 49 are arcuate slots 50 having their radial walls 51 slanted in the same direction. The arcuate slots 50 provide an approximately linear increase in the amount of air that can flow through the air flow control 49 as the upper plate 42 rotates from the first to the second position, and the slanted walls cause the air passing through the air flow control to form a vortex in the mixing chamber 24 and the nozzle section 36 thereby enhancing the mixing of the air with the atomized fuel.

In the embodiment of FIGS. 2 and 6, gasoline, or another liquid fuel suitable for combustion in an internal combustion engine, is provided to an annular fuel conduit 55 through a passage or tube 56 communicatively coupled to a fuel port 57 in the interior of sleeve 60. A metering valve 61 controls or meters the quantity of fuel passing through the tube 56 and into the annular conduit 55. The valve 61 is positioned as close as possible to the fuel port 57 to minimize the possibility of premature vaporization or atomization of the fuel by the manifold or cylinder vacuum in the portion of the tube 56 between the valve 61 and the fuel port 57. The amount of fuel entering the fuel conduit 55 through the valve 61 is controlled by movement of a second arm 62 extending from the valve 61 and through a second slot 63 in the housing 21. The second arm 62 and the arm 47 which operates the air flow control 40 may be interlinked and interconnected to the accelerator pedal to thus provide increased air flow and increased liquid fuel flow or decreased air flow and decreased liquid fuel flow depending on the operator's control of the accelerator pedal.

The fuel is atomized in the mixing chamber 24 by means of sonic vibrational energy supplied to the sonic probe 45 by a transducer 65. The transducer 65 is mounted in housing 21 with the longitudinal axis thereof coincident with the longitudinal axis of the housing 21. The transducer 65 is of conventional design, preferably a standard piezoelectric sonic generator 67 comprising an upper block 68, a piezoelectric ceramic plate 69, an intermediate aluminum transducer mounting plate 70, a second piezoelectric ceramic plate 71 and a lower block 72. However, other transducers such as magnetostriction-type transducers would provide suitable sonic longitudinal vibrations to the sonic probe 45. The transducer 65 is energized by means of a battery supplied power oscillator 75, impedance matched to the transducer 65.

The frequency of the sonic energy used in the apparatus does not appear to be critical insofar as atomizing effect is concerned. A specific device embodying the

invention has been successfully tested at frequencies of 20 to 40 kHz, but the operable range appears to extend from well below 10 kHz to around 100 kHz. As a practical matter, frequencies in the audible range (below approximately 18 kHz) should be avoided to prevent operator annoyance.

In the embodiment of FIG. 2, the sonic probe 45 is mounted to the bottom 66 of the transducer 65 with the longitudinal axis of the probe 45 incident with the longitudinal axis of the transducer 65 and of the housing 21. The sonic probe 45, preferably has a circular cross-section, the diameter thereof gradually decreasing from a cylindrical upper portion 80 to a cylindrical central portion 81. The lower portion 82 of the sonic probe 45 is preferably flared with the diameter of the flared portion exponentially increasing from the diameter of the central portion 81 to the diameter of the bottom 83 of the sonic probe 45.

A sonic tip 85, having a circular cross-section, is mounted to the bottom 83 of the sonic probe 45. The slanted outer face 86 of the sonic tip 85 is a smooth continuation of the surface at the bottom of the sonic probe 45, and the diameter of the sonic tip 85 preferably increases exponentially from the diameter of the top 88 of the sonic tip 85 to the diameter of a narrow circumscribing edge, preferably a cylindrical rim 89, at the bottom of the sonic tip 85. In one embodiment of the sonic tip 85, the diameters of top 88 and the lower face 90 of the sonic tip 85 are three-quarters of an inch and 1 inch, respectively, and the thickness of the narrow rim 89 is one thirty-second of an inch. In another embodiment the narrow rim 89 has a knife edge with substantially zero thickness. The lower face 90 of the sonic tip 85 preferably extends in a plane perpendicular to the longitudinal axis of the sonic probe 45, but it may have other forms, as described below. The clearance between the rim 89 and the curving walls 35 of the nozzle section 36 forms an annular passage 95 in which the air stream drawn through air flow control 40 mixes turbulently with the atomized fuel discharged from the sonic tip 85 of sonic probe 45.

Although the sonic probe 45 and sonic tip 85 are not necessarily of conventional design, they can be constructed of conventional sonic probe materials. Titanium has been found to be a particularly advantageous material from which to construct the sonic tip 85 although other light weight materials may be used which are not affected by the fuel and which will withstand the stresses that are imposed without breaking.

The fuel is atomized by sonic probe 45 as it flows from the annular fuel conduit 55 and migrates along the slanted face 86 and the lower face 90 of the sonic tip 85. The fuel conduit 57 is defined by the sonic probe 45 and a cylindrical sleeve 60 mounted below the lower plate 41 of the air flow control 40 with the longitudinal axis thereof incident with the longitudinal axis of the housing 21. The cylindrical sleeve 60 has an outer diameter approximately equal to the diameter of the flared bottom 83 of the sonic probe 45. The diameter of the cylindrical interior surface 102 of the sleeve 60 is slightly greater than the diameter of the sonic probe 45 over the length of the probe 45 but is matched to provide the fuel conduit 55 between the probe 45 and the interior surface 102 of the sleeve. For example, the clearance at the controlling faces between the sonic probe 45 and the sleeve 60 is preferably on the order of about a half to several thousandths of an inch. This

clearance could be used as a primary or secondary means of controlling the flow of fuel, and it has been found that if the matching faces are in contact with each other, flow through them will cease, but even in this closed condition energizing of the probe will cause flow to commence provided the fuel is under pressure. The upper end of the fuel conduit 57 is sealed with an O ring 103 which fits into an O ring channel 104 in the interior surface 102 of the sleeve 60 and abuts against the sonic probe 45. The lower end of the fuel conduit 57 is open to the mixing chamber 24 through an annular opening 105 between the sleeve 60 and the sonic tip 85. The height of the opening 105 is quite small, in operation preferably on the order of two thousandths of an inch. Means can also be provided for axially adjusting the position of the sleeve 60 with respect to the sonic probe 45 to vary the opening 105.

It will be readily apparent to one skilled in the art of sonic probes that the lengths of the transducer 65, the sonic probe 45 and the sonic tip 85 can be varied and matched to produce maximum amplitude vibration at the lower face 90 of the sonic tip 85, depending in part upon the resonant frequency of the transducer 65 and the velocity of the pressure wave in the material. The combined length of the sonic probe 45 and the sonic tip 85 can be an integral number of half wavelengths at the resonant frequency of the transducer 65 if the interface between the transducer 65 and the sonic probe 45 is at a pressure node (i.e., velocity antinode). To minimize frictional heating or abrasive wear on the O ring 103, it can be positioned at a velocity node of the sonic probe 45. In the preferred embodiment of the apparatus, it is functionally desirable to minimize the length of the sonic probe. Therefore, the aluminum plate 70 of the transducer 65 serves as the nodal support for the transducer 65, and the distance from the lower face 66 of the lower block 72 to the lower face 90 of the sonic tip 85 is approximately one-half wavelength of sound in the material of the probe at the resonant frequency of the transducer 55. In this embodiment, the lower face 90 of the sonic tip 85 is at maximum amplitude vibration. The O ring 103 is located approximately one-quarter wavelength from the lower face 80 of the sonic tip 85.

As was noted above, the apparatus of the present invention can replace a conventional carburetor for a reciprocating internal combustion engine of an automobile. Now, referring to FIG. 6, the apparatus of FIGS. 1-5 is shown schematically in relation to such an engine 120. The apparatus 20 is mounted to the engine 120 between the air filter 121 and the intake manifold 122. The air flow control 49 and the fuel metering valve 61 of the apparatus 20 are mechanically linked to the accelerator pedal 123 by linkage means 124. When the pedal 123 is depressed, the linkage means 124 causes the air flow control 49 to open a controlled amount, admitting intake air into the mixing chamber 24, and causes valve 61 to meter the appropriate amount of fuel into the fuel conduit 55. The battery supplied power oscillator 75 energizes the transducer 65 providing sonic vibrational energy to the sonic tip 85. The intake air passing through the mixing chamber 24 mixes with the highly atomized fuel emitting from the sonic tip 85, and this fuel-air mixture passes through the nozzle section 36 into the intake manifold 122 and on to the appropriate cylinder 125 of the engine 120 where it is ignited.

The apparatus shown in FIG. 2 was mounted on an automobile engine operating with near stoichiometric quantities of air and fuel. The more uniform fuel-air mixture produced by the apparatus resulted in more complete burning of the fuel, as evidenced by preliminary tests showing very low values of incomplete combustion products such as carbon monoxide and unburned hydrocarbons in the exhaust gas. Furthermore, the nitrous oxide content of the exhaust gas was low because most of the oxygen in the intake air was consumed in the efficient burning of the fuel, thereby substantially reducing the oxygen available for combination with the atmospheric nitrogen. The nitrous oxides were also low because of the reduced maximum temperature of the combustion gas and the shortened residence time of the combustion gas at high temperatures, as discussed earlier.

Aside from reducing air pollution, use of the apparatus of the invention in place of a conventional carburetor provides the additional benefit of improved fuel economy because of the efficient burning of the more uniform fuel-air mixture.

The primary factor contributing to the uniform fuel-air mixture produced by the apparatus of the invention is undoubtedly the fine atomization resulting from concentrated application of sonic energy to a thin film of liquid fuel flowing across the atomizing surface of the sonic probe.

This fine atomization is apparently produced by a combination of physical agitation of the fuel film, primarily by cavitation caused by the motion of the atomizing surface, and increased molecular energy due to emission of sonic energy from the atomizing surface. In a sense, the first effect is macroscopic, and the second is microscopic. The cavitation effect is probably more important at low sonic frequencies, and the sonic irradiation effect more important at the higher frequencies.

The configuration of the preferred embodiments of the invention, particularly the manner of presenting the liquid fuel to the atomizing surface and the relation of that surface to the air stream, appear to have a significant effect on the degree of atomization produced. This is best explained by referring to FIG. 5, which is a closeup view of the sonic tip area of the embodiment of FIG. 2. As shown, a thin film of fuel 110 flows from annular fuel conduit 55 through the annular opening 105 between the sleeve 60 and the sonic tip 85 onto the flared atomizing surface 86.

Because the sonic vibrations in the sonic probe are longitudinal, only the component of surface 86 that is perpendicular to the axis of the probe does any work on the liquid film. Accordingly, it is desirable to have the surface 86 flare broadly, preferably to a 90° angle at the region adjacent circumscribing edge 89.

In addition, it is important that the fuel flow in a thin film and remain in contact with the atomizing surface long enough to receive sufficient energy to atomize and vaporize before it enters the air stream. This result is accomplished by controlling the clearance between the sleeve 60 and sonic tip 85 to produce a thin film and by directing the air stream against the atomizing surface 86 and across or past the circumscribing edge 89. The nominal clearance between sleeve 60 and tip 85 may be two-thousandths of an inch, for example, so the maximum thickness of the liquid film at that point is correspondingly two-thousandths of an inch.

As film 110 migrates across the flared atomizing surface 86, the static pressure of the air stream tends to hold it against the vibrating surface so that it continues to perform work on and raise the energy level of the liquid. It is believed that the sonic vibrational energy draws out or reduces the thickness of the film 110 and continuously atomizes it until, at the circumscribing edge 89 of sonic tip 85, the film is possibly only several molecules in thickness. It is further believed that most of the very thin film of fuel 110 is discharged or emitted, in a highly atomized state, from the sonic tip 85 at or near the edge 89, although a small amount may flow around the edge and towards the center of the lower face 90 of sonic tip 85 where it is likewise discharged or emitted.

Other features of the preferred embodiments of the invention then appear to have a cumulative effect that greatly enhances the subsequent vaporization and intimate mixing of the fuel with the air stream. For example, the highly atomized fuel emitted from the sonic tip 85 is mixed with the intake air as it passes by edge 89 and then through the annular opening 105 between the tip 85 and the walls 35 of the nozzle section 36. The walls of nozzle section 36 preferably converge exponentially to promote substantially laminar flow of the air stream adjacent the walls to the throat of the nozzle. This laminar flow reduces contact of the atomized and vaporized fuel in the fuel-air mixture with the walls 35 to minimize condensation of the fuel onto the relatively cold surface thereof.

At the same time, the converging flow tends to intimately mix the atomized fuel with the air stream. In addition, the mixture flowing through nozzle 36 is exposed to sonic energy radiated from the face of sonic tip 85. The nozzle region, as well as the manifold passageway below, thus forms an ensonified region in which the sonic energy radiated by the face of the probe appears to perform additional work on the mixture to further atomize and vaporize the fuel and to move thoroughly mix it with the air. As noted earlier, the mixing is further enhanced by the vortex flow of the air caused by the slanted walls 51 of the arcuate slots 50 in the throttle plates 41 and 42. It is also believed that the sonic vibrations that are radiated from the face of the sonic tip 85 are also transmitted on through the manifold chamber into the cylinders while the inlet ports are open. These vibrations within the chambers downstream of the mixing areas serve to maintain the homogeneity of the mixture and serve to make the vaporized mixture more efficient as a conductor of heat in accord with the well-known physical phenomenon that a vibrating fluid is a better conductor of energy.

As a consequence, therefore, of all the features of the above-described preferred embodiment of the invention, not only is the liquid fuel emitted initially in highly atomized and vaporized form, but also its vaporization and mixing is subsequently enhanced and recondensation minimized.

Other embodiments of the sonic probe will accomplish the above objectives and purposes. For example, FIG. 7 shows another embodiment of a sonic probe 150 for the apparatus of the present invention. The sonic probe 150 and the sleeve 151 resemble the sonic probe 45 and the sleeve 60 of FIG. 2, except that the flared portion 152 of the sonic probe 150 is a sonic tip 153. The sonic tip 153 has a circular cross-section, the diameter of which increases exponentially from the diame-

ter of the cylindrical portion 154 of the sonic probe 150 to the lower face 155 of the sonic tip 153.

FIG. 8 (a) and (b) shows still another embodiment of a sonic tip 160, identical to the sonic tip 153 of FIG. 7, except that a small cone-like protrusion 161 projects downwardly from the center of the lower face 162 of the sonic tip 160.

FIG. 9 (a) and (b) shows still another embodiment of a sonic tip 170 identical to the sonic tip 153 of FIG. 7, except that a plurality of evenly spaced cone-like protrusions 171 project downwardly from the lower face 172 of the sonic tip 170.

FIG. 10 shows still another embodiment of a sonic probe 180 for the apparatus of the present invention. The liquid fuel is concurrently supplied from tube 181 into an annular fuel conduit 182 (identical to the annular fuel conduit 55 described with respect to the apparatus of FIG. 2) and a central fuel channel 183. The channel 183 passes down the longitudinal axis of the sonic probe 180 and terminates at the lower face 184 of a sonic tip 185. The sonic tip 185 is identical to the sonic tip 153 of FIG. 7, except for a cone-like stub 186 extending downwardly from the center of the lower face 184 of the sonic tip 185. In addition to the fuel flowing from the fuel conduit 182, as described above, the fuel passes down the channel 183, and a film of fuel migrates along the surface 189 of the cone-like stub 186 and outwardly towards the perimeter of the lower face 184 of the sonic tip 185.

FIG. 11 shows still another embodiment of a sonic probe 190, similar in detail to the sonic probe 180 of FIG. 10, except that a second sonic tip 191 extends downwardly from the center of the lower face 192 of a sonic tip 193. The second sonic tip 191 has a circular cross-section, the diameter of which increases exponentially from the top 194 to the lower face 193 thereof. The fuel passing down the channel 196 migrates outward across face 192 and also downward across flared surface 196 of the second sonic tip 191.

FIG. 12 shows still another embodiment of a sonic probe 200. The sonic probe 200 and the sleeve 201 are similar to the sonic probe 150 and the sleeve 151 of FIG. 7, except that the bottom flared portion 202 of the sonic probe 200 is coupled to an inverted truncated cone portion 203 having a relatively shallow base angle 204. The circumscribing edge 205 of the cone is a knife edge with substantially zero thickness.

FIG. 13 is still another embodiment of a sonic probe 210, similar to the sonic probe 182 of FIG. 10, except that a plurality of second fuel channels 211 extend from a plurality of openings 212 in the lower face 213 of the sonic probe 210 and intersect a central fuel channel 214.

Although the embodiments of the apparatus of the invention discussed above utilize an annular conduit to provide a thin film of liquid fuel to the flared portion of a sonic probe, the invention is not limited to these elements. For example, FIG. 14 shows another embodiment of the apparatus of the invention comprising a housing 220, defining passage 221 for the flow of air therethrough. A sonic transducer 222, as described above, is mounted in the center of the lower portion 223 of the passage 221. A portion of the air entering the passage 221 through an air flow control 224, as described above, impinges upon the upstream face 225 of the transducer 222 and flows past the circumscribing edge 226 thereof.

A thin film 227 of fuel is provided to the upstream face 225 of the transducer 222 through an opening 228 in the end of a tube 229 positioned above the center of the face 225. The flow of fuel through the tube 229 is controlled by a valve 230 actuated as described earlier. The fuel is held against the upstream face 225 of the transducer 222 by the flow of air and is highly atomized by sonic energy from the transducer 222 as it travels from the center towards the circumscribing edge 226 of the face 225. The highly atomized fuel mixes with the flow of air and the resulting fuel air mixture passes through the annular passage 231 around the transducer and out an opening 232 in the bottom of the housing 220.

Results of dynamometer tests of the vehicle equipped with a standard carburetor are shown in TABLE II for comparison. The engine of the test vehicle presented a particularly difficult nitrogen oxides ( $\text{NO}_x$ ) problem because of its very high 12.5 : 1 compression ratio. The engine was also equipped with the so-called Chrysler "clean-air" package, which provides spark timing settings of from 45° before Top Dead Center (TDC) to 9° after TDC. Thus one could expect low carbon monoxide (CO) and low hydrocarbon (HC) percentages in the exhaust, but high  $\text{NO}_x$  because of the pressures and temperatures resulting from the high compressions. These expectations are borne out by the figures in TABLE II. The equivalent figures in TABLE I indicate that the device of the present invention produces substantial reductions in  $\text{NO}_x$ , while still maintaining respectable values of CO and HC.

FIGS. 15 through 20 portray various aspects of another preferred embodiment that includes novel means for positively controlling the fuel and air supply under all load and speed conditions. An apparatus conforming to this embodiment has been installed on an automobile engine and successfully operated in both laboratory and road environments. Exhaust gas analyses have indicated significant reductions of carbon monoxide, nitrous oxides and unburned hydrocarbons in comparison with results using a conventional carburetor.

For example, tests have been conducted by an independent testing agency on a 1970 Mercedes Benz Model 220 automobile with standard transmission. The tests were conducted on a Clayton water-brake dynamometer set to absorb 12 horsepower at 50 miles per hour. The tests were run with the apparatus of the present invention in place of the standard carburetor. Ten timed tests simulating various road conditions were run. Exhaust gas samples taken for each test were analyzed for nitrous oxides, carbon monoxide and unburned hydrocarbons, with results as shown in TABLE I. The engine was cold for tests 1 through 5 and hot for the remaining tests. All acceleration tests were sampled for the length of time to reach desired speed. Sampling times during deceleration tests were governed by the loading of the dynamometer to slow the vehicle down.

TABLE I

| Test No. | Condition      | Time              | Exhaust $\text{NO}_x$ (ppm) | Exhaust CO (%) | Exhaust Total Hydrocarbons (%) |
|----------|----------------|-------------------|-----------------------------|----------------|--------------------------------|
| 1        | Idle (800 RPM) | 2 min.            | 42.0                        | 0.20           | 0.23                           |
| 2        | 0-60 mph       | 12 sec. (approx.) | 272                         | 1.64           | 0.94                           |
| 3        | 60-20 mph      | 20 sec. (approx.) | 262                         | 0.41           | 0.24                           |
| 4        | 60 mph         | 2 min.            | 271                         | 0.81           | 0.22                           |

|    |                     |                   |      |      |      |
|----|---------------------|-------------------|------|------|------|
| 5  | (4th gear) 60 mph   | 2 min.            | 173  | 0.35 | 0.07 |
| 6  | (3rd gear) 0-60 mph | 12 sec. (approx.) | 256  | 1.39 | 0.84 |
| 7  | 60-20 mph           | 20 sec. (approx.) | 264  | 0.77 | 0.45 |
| 8  | 60 mph (4th gear)   | 2 min.            | 254  | 0.74 | 0.27 |
| 9  | 60 mph (3rd gear)   | 2 min.            | 316  | 0.51 | 0.03 |
| 10 | Idle (800 RPM)      | 2 min.            | 13.3 | 0.15 | 0.04 |

TABLE II

| No. | Condition         | Time              | Exhaust $\text{NO}_x$ (ppm) | Exhaust CO (%) | Exhaust Total Hydrocarbons (%) |
|-----|-------------------|-------------------|-----------------------------|----------------|--------------------------------|
| 15  | Idle (800 RPM)    | 2 min.            | 25                          | 7.23           | 7.81                           |
| 2   | 0-60 mph          | 12 sec. (approx.) | 882                         | 0.35           | 0.18                           |
| 3   | 60-20 mph         | 20 sec. (approx.) | 362                         | 1.02           | 0.82                           |
| 20  | 60 mph (4th gear) | 2 min.            | 1290                        | 0.27           | 0.10                           |
| 5   | 60 mph (3rd gear) | 2 min.            | 800                         | 0.71           | 0.48                           |
| 6   | 0-60 mph          | 12 sec. (approx.) | 814                         | 0.51           | 0.35                           |
| 25  | 60-20 mph         | 20 sec. (approx.) | 590                         | 0.51           | 0.21                           |
| 8   | 60 mph (4th gear) | 2 min.            | 879                         | 0.32           | 0.11                           |
| 9   | 60 mph (3rd gear) | 2 min.            | 1030                        | 0.23           | 0.11                           |
| 30  | Idle (800 RPM)    | 2 min.            | 52                          | 0.15           | 0.07                           |

Referring to FIGS. 15 through 20, this embodiment includes a housing 310 having a main body 312 and an inlet duct 314 which together form an internal passageway 316 with an inlet 318 for air and an outlet 320 for a mixture of fuel and air. The inlet duct 314 carries a throttle valve such as a rotary shutter valve 322 pivotally mounted for reciprocal rotation between open and shut positions by means of lever arm 324.

The main body 310 of housing 312 has sidewalls 326, preferably of circular interior cross-section, a relatively thick closed end 328, and a drilled and tapped base 330 for bolting to a flanged inlet manifold 331 of an internal combustion engine. The inside diameter of inlet manifold 331 is preferably of less diameter than the inside surface of sidewalls 26 to provide a restricted passageway for increasing turbulence and improving the mixture of fuel and air.

Inside body 312 of housing 310 is an elongated electroacoustic transducer 332 comprising a cylindrical steel upper block 334, piezo-electric crystals 336 and 338 separated by a brass ring 340, and an aluminum acoustic probe 342 tapering elliptically or parabolically to a high-velocity tip 344 of reduced diameter. The upper end of acoustic probe 342 has a flange 333 for mounting transducer 332 in annular recess 335 between upper half 337 and lower half 339 of body 312. A circular row of holes 337 in flange 33 permit air flow through the upper portion of inlet 319 and around the piezo-electric crystals to cool them.

Electrical lead 341 connects brass ring 340 to one side of the output of a conventionally designed electronic power oscillator. The output of the oscillator is returned through ground to flange 333 and thence through stack compression bolt 339 to the upper transducer block 334. As a consequence, the upper face of piezo-electric crystal 336 and the lower face of crystal 338 are at ground potential, and their respective lower

and upper faces are at the alternating voltage output of the oscillator.

Another possible way to achieve the good electrical contact between crystals provided by brass ring 340 with even better acoustic coupling at their interface is to cement the two crystals together, using an epoxy glue mixed with sufficient powdered metal, preferably silver, to make a conductive bond.

The dimensions of the elements of transducer 332 are selected so that the axial distance from the upper end of upper block 334 to the midplane of flange 333 is equivalent to one-quarter wavelength at the frequency of the oscillator, and the axial distance from flange 333 to tip 344 of acoustic probe 342 is also equivalent to one-quarter wavelength. The overall length of transducer 332 is thus one-half wavelength.

If the crystals 336 and 338 are mounted so that lower face of crystal 336 is of the same polarity as the upper face of crystal 338, they will expand and contract simultaneously in response to the alternating voltage from the power oscillator. Since both crystals are on the same side of the mounting flange in this embodiment, the transducer will vibrate longitudinally, with a velocity node at flange 33 and antinodes at the upper end of block 334 and at probe tip 344. Because the tapered end of probe 342 acts as an inverted horn or velocity transformer, the amplitude of vibration of tip 344 is much greater than the vibrational amplitude of the upper end of the transducer.

A thin disk 346, preferably made of titanium, is securely fastened to probe 344 by stud 343 and nut 345 to provide a vibratory surface 348 for atomizing and mixing a thin film of fuel into a stream of air flowing through internal passageway 316. Disk 346 preferably has a beveled edge 350 making an acute angle with surface 348 to enhance upward and outward projection of fuel particles into the flowing air stream. The size of disk 346 in relation to the internal diameters of sidewalls 326 and outlet 322 and its distance from base 330 affect the thoroughness of mixing of the atomized fuel with the airstream. An optimum relation between these dimensions can be developed experimentally for a given engine.

For illustration, in an operative version of this embodiment, disk 346 has an outside diameter of 1.26 inches and a thickness of 0.03 inch. The working area of the disk is roughly three-quarters of a square inch, not counting the downstream face which appears to contribute some atomizing action. Highly efficient atomizing action has been obtained with an oscillator frequency of 20.3 kHz and a measured power input to the piezoelectric crystal of slightly less than 4 watts. This indicates that the configuration of this embodiment produces exceptionally efficient atomization.

Fuel is supplied under pressure by a fuel pump (not shown) and a fuel line 347 to inlet 352 of a fuel conduit 354 in a boss 356 on the side of housing 310. Fuel conduit 354 leads through a fuel valve body 358 mounted integrally within boss 356, then through a short tube 360 inserted through the inner surface of sidewall 26, a length of flexible tubing 362 slipped over and bonded to short tube 360 and over a second short tube 364 inserted in the side of a means for distributing fuel in a thin film across vibratory surface 348.

Referring particularly to FIGS. 18-20, the fuel distributing means comprises a separate ring-shaped member 366 slidably fitted around the tip 344 of

acoustic probe 342. A biasing means such as coil spring 368 urges one annular face of ring member 366 axially into contact with vibratory surface 348. An annular passageway 374 in ring member 366 connects with the downstream end of short tube 364 and conveys fuel circumferentially for uniform distribution through circumferentially spaced openings 370 in annular ring face 372 and thence to flow radially outward in a thin film across vibratory surface 348.

To provide space for the outward flow of fuel between the annular face of ring member 366 and vibratory surface 348, particularly with a stiff spring 368, a portion of the annular face extending radially outward from holes 370 may be slightly relieved to form a narrow axial gap between annular face 372 and vibratory surface 348 opening radially outward (See FIG. 20). The width of the gap (i.e., the depth of the relief) should be no more than 0.001 to 0.002 inch to insure that the fuel flows outwardly in a thin film.

In actual practice it has been found that no relief is necessary, and the device can be operated, at least in the vertical position, with ring member 366 merely resting on vibratory surface 348 without any spring. Apparently, sufficient clearance for fuel flow is generated between the annular face of the ring and the vibratory surface by the vibration of surface 348.

The amount of fuel flowing through conduit 354 is controlled by a fuel valve such as reverse needle valve 376 mounted in valve body 358 and having an elongated stem 378 extending externally of boss 356 through a support sleeve 380 to culminate in a slotted end 382. A cylindrical bellows 384 coaxially surrounds valve stem 378 and is sealingly attached to fuel valve body 358 at its inner end to form a variable volume chamber connected to fuel conduit 354 and the inlet of valve 376. The outer end of bellows 384 is sealed to a plate 386 fixed to valve stem 378. A coil spring 388 located inside bellows 384 urges a cam follower wheel 390, mounted in slotted end 382 of valve stem 378, against means, such as a sliding cam 392 for changing simultaneously the flow area through fuel valve body 358 and the volume of bellows 384 by axial movement of valve stem 378.

The movement of sliding cam 392 is synchronized with movement of throttle valve 322 by means of link member 394 and arms 395 and 397, joining cam 392 to lever arm 324. The shape of cam 392 is synchronized with movement of throttle valve 322 under an assumed load condition. If the device of the invention is being used in conjunction with an automobile engine, the throttle and cam settings are controlled by a second link member 396 joining cam 392 through a bellcrank 399 to an accelerator pedal (not shown) through conventional linkages.

In FIG. 15, both air throttle valve 322 and fuel poppet valve 376 are shown in shut position. (Even when nominally shut, air valve 322 will be open a fraction to permit inlet of enough air for engine idle.) It is apparent that counterclockwise movement of lever arm 324 will tend to open throttle valve 322 and fuel poppet valve 376 and to contract the volume of bellows 384. Conversely, when the throttle valve 322 and fuel valve 376 are open, clockwise movement of lever arm 324 will shut both valves and expand bellows 384.

Because bellows 384 opens at its inner end to fuel conduit 354, it serves as a reservoir and acts as an accelerator pump to supply additional fuel through valve

376 as the valve opens. Since bellows 384 is connected to the main fuel conduit rather than to a bypass line and separate spray jet, as is the accelerator pump in a conventional carburetor, it serves the additional function of accepting incoming fuel as valve 376 shuts and thus of momentarily diverting flow from the fuel distributing means.

This additional function is highly beneficial in that it effectively stops fuel flow to the engine as soon as air throttle valve 322 starts to shut, eliminating the transient enrichment with consequent backfiring and pollution generation that often occurs with conventional carburetors upon sudden deceleration. Furthermore, once poppet valve 376 has shut, fuel is stopped positively from flowing to the engine.

Because of this positive stoppage, the fuel in the embodiment of FIGS. 15-20 cannot be shut off completely when throttle valve 322 is shut if the engine must idle at closed throttle, as is true for automobile engines. It is difficult to adjust valve 376 for metering both large and small flow rates, however; so the use of a single valve for operating both at high speed and at idle is unsatisfactory. This problem may be resolved by incorporating a bypass valve 398 to supply fuel under idle conditions.

Inlet channel 400 and outlet channel 402 connect valve body 398 in parallel with main fuel valve body 358. Mounted in auxiliary valve body 398 is a small reverse-needle valve 404 with an elongated stem 406 connected through extensions at its outer end to a flexible diaphragm 408 sealingly supported at its edges in a rigid capsule 410.

Valve stem 406 is free to move axially to open or shut needle valve 404 in response to a pressure differential across diaphragm 408. Reverse-needle valve 404 is normally biased in the open direction by coil spring 414 on the valve side of diaphragm 408. A vacuum line 401 leads from the engine intake manifold to a port opening into capsule 410 on the side of diaphragm 408 opposite valve 404; so that side of the diaphragm is exposed to manifold vacuum. The chamber formed between the other side of diaphragm 408 and the outside of capsule 410 may be sealed at some positive pressure or, preferably, be vented to atmosphere.

The axial spacing between diaphragm 408 and the valve seat of auxiliary valve body 398 can be adjusted to cause needle valve 404 to almost seat in response to the manifold vacuum under idle conditions, which may typically be in the range 12 - 24 inches of mercury. If the engine begins to stall, the manifold vacuum will drop sharply, causing needle valve 404 to open and supply additional fuel. On the other hand, if the engine starts to run too fast, the manifold vacuum will increase because throttle valve 322 is shut, causing needle valve 404 to shut and stop all fuel flow until the manifold vacuum drops again.

Vacuum-operated needle valve 404 thus provides a self-regulating action not found in fixed-adjustment idle valves of conventional carburetors. Needle valve 404 also contributes a fuel-enrichment function under load conditions. As described earlier, for a given throttle valve setting, engine speed decreases with increasing load. The pistons then draw less air per minute into the cylinders, and the manifold vacuum drops. Fuel flow through the main fuel poppet valve 376 remains constant because its setting is directly linked to that of the throttle. The auxiliary needle valve 404 opens,

however, in response to the drop in manifold vacuum and supplies additional fuel to the distribution means 366.

In some applications it may be desirable to control the main fuel valve of the invention by a means more precisely responsive to the rate of air flow through the device than is the direct mechanical connection to the throttle valve. For example, the constant fuel flow rate through valve 376 provided at fixed throttle settings by the embodiment of FIGS. 15-20 produces increased fuel-air ratios with increasing loads to, in effect, enrich the mixture. Coupled with the increased flow through needle valve 404, this may result in too rich a mixture for optimum combustion, with a consequent increase in pollutant emission.

Controlling the flow through valve 376 as a direct function of air flow may be accomplished by substituting a pressure-type actuator for the cam and follower arrangement shown in the drawings. Throat pressures in a venturi installed in inlet duct 314 upstream of throttle valve 322 would be inversely proportional to air flow and could be used to operate the pressure-type actuator for valve 376 in a manner similar to that used in conventional pressure-type carburetors for supercharged reciprocating aircraft engines.

It will be appreciated that many variations in the form and arrangement of the above-described embodiments are possible without departing from the scope of the invention. For example, a bell crank may be substituted for cam 392 and follower 390, a piston and cylinder for bellows 384 or for diaphragm 408 and capsule 410, to name just a few. Furthermore, it will be understood that the mechanical arrangement of the devices in the drawings is presented to some extent in schematic form for simplicity, and that modifications obvious to those skilled in the art may be necessary to permit assembly and adjustment of an actual device according to the invention.

As discussed above, the apparatus of the present invention has application in providing a highly effective gasoline-air mixture for combustion in the cylinders of a reciprocating internal combustion engine. In a similar manner as that described above, jet fuel can be effectively mixed with air prior to combustion of the fuel-air mixture in the combustion chamber of a jet engine. The apparatus has further application to atomize and vaporize diesel fuel for combustion in a diesel engine.

Other modifications and variations of the apparatus will be apparent to those skilled in the art, and they may be made without departing from the spirit and scope of the present invention.

I claim:

1. A device for delivering positively controlled amounts of air and highly atomized fuel to an internal combustion engine comprising:

- a. a housing having an internal passageway with an inlet for a stream of air and an outlet for the stream of air mixed with highly atomized fuel;
- b. a sonic fuel atomizer, the atomizer including
  - i. a sonic transducer for converting alternating electric energy to longitudinal vibrations of a downstream-facing surface of the transducer,
  - ii. an elongated velocity transforming probe having a large end and a small end and acoustically coupled at its large end to the downstream-facing surface of the transducer for amplifying the vibrations of said surface, and

- iii. an atomizing tip attached to the small end of the probe, the tip having an upstream-facing longitudinally vibrating fuel atomizing surface in the passageway between the inlet and the outlet and extending radially outward from the end of the probe, a circular circumscribing edge bounding the upstream-facing fuel atomizing surface of substantially larger diameter than the small end of the probe, and a downstream-facing surface;
- c. a fuel distribution member surrounding the small end of the probe, said member having an annular surface positioned in opposed, closely-spaced relation to a portion of the upstream-facing surface of the tip for forming an annular fuel conduit between the two surfaces, the extent of the conduit outward between the surfaces being substantially greater than the distance between the surfaces; and
- d. means for supplying controlled amounts of liquid fuel under pressure to the annular fuel conduit for flow in a thin film outward across the upstream-facing surface of the tip, the spacing between the surfaces of the annular fuel conduit being close enough so that the amount of fuel flow will be substantially unaffected by pressure variations within the passageway, whereby the thin film of fuel will be substantially completely atomized from the upstream-facing, longitudinally vibrating surface of the tip for mixture with the stream of air from the inlet, and the fuel-air mixture will be further mixed by acoustic energy radiated from the downstream-facing surface of the tip.
2. The device of claim 1 further comprising a throttle valve located upstream of the atomizing tip for controlling the amount of air through the passageway in predetermined relation to the amount of fuel supplied to the annular fuel conduit.
3. The device of claim 2 wherein the spacing between the annular surface of the fuel distribution member and the upstream-facing surface of the atomizing tip is between approximately 0.0005 inch and approximately 0.002 inch.
4. The device of claim 1 wherein the fuel distribution member comprises a ring-shaped member adapted to loosely surround the small end of the probe and to overlie a portion of the upstream-facing surface of the atomizing tip.
5. The device of claim 4 wherein said ring-shaped member includes an internal annular fuel passageway connected to the means for supplying fuel under pressure and a plurality of circumferentially spaced openings leading from the annular passageway through said annular surface for distributing fuel evenly across said vibratory surface.
6. The device of claim 4 further comprising a biasing means for resiliently urging the annular surface of said

ring-shaped member against said vibratory surface.

7. The device of claim 6 wherein said biasing means comprises a coil spring surrounding said acoustic probe and bearing against the face of said ring-shaped member opposite to said annular surface.

8. The device of claim 1 wherein the fuel distribution member comprises:

a. a coaxial sleeve surrounding the probe, the internal and downstream surfaces of the sleeve conforming to the outer surface of the probe and the abutting upstream-facing surface of the tip but closely spaced therefrom to define a narrow annular fuel conduit, the sleeve having a passage connected to the means for supplying fuel under pressure with an inlet port opening in the internal surface of the sleeve for conducting the fuel into the annular conduit and

b. means for flexibly sealing the annular conduit between the internal surface of the sleeve and the outer surface of the probe, the sealing means being located between the inlet port in the sleeve and the large end of the probe.

9. The device of claim 8 wherein the fuel inlet port is axially located approximately one-quarter wavelength from the small end of the probe.

10. The device of claim 8 further comprising means for adjusting the position of the sleeve axially with respect to the probe, whereby the spacing between the downstream surface of the sleeve and the upstream-facing surface of the atomizing tip can be correspondingly adjusted.

11. The device of claim 1 wherein the means for supplying controlled amounts of fuel comprises:

a. a conduit having an inlet exterior of the housing and leading to the fuel distribution means;

b. a main fuel valve in said conduit for controlling the delivery rate of fuel through the conduit, the main fuel valve including a stem movable axially for opening or shutting the valve;

c. a variable volume chamber surrounding the stem of the main fuel valve to serve as a fuel reservoir, the chamber having a movable end wall connected to the valve stem for movement therewith;

d. actuator means connected to the throttle valve and the main fuel valve for changing the flow area through the fuel valve and the volume of the variable volume chamber in predetermined relation to variations of the flow of air through the device; and

e. an auxiliary fuel valve connected in parallel with the main fuel valve and responsive to absolute pressure in the internal passageway downstream of the throttle valve for supplying fuel in direct relation to changes in said absolute pressure.

\* \* \* \* \*

UNITED STATES PATENT OFFICE  
CERTIFICATE OF CORRECTION

Patent No. 3,756,575

Dated September 4, 1973

Inventor(s) Eric C. Cottell

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Col. 1, line 27: change "on" to --an--.

Col. 6, line 30: change "chambe" to --chamber--.

Col. 10, line 47: change "mateials" to --materials--.

Col. 16, Table I, item 8, col. 5: change "0.74" to --0.72--.

Signed and sealed this 18th day of December 1973.

(SEAL)

Attest:

EDWARD M. FLETCHER, JR.  
Attesting Officer

RENE D. TEGTMEYER  
Acting Commissioner of Patents