May 31, 1966 R. H. HASS 3,253,400

EXHAUST TREATMENT APPARATUS AND METHOD

Filed Aug. 7, 1961 3 Sheets-Sheet 1

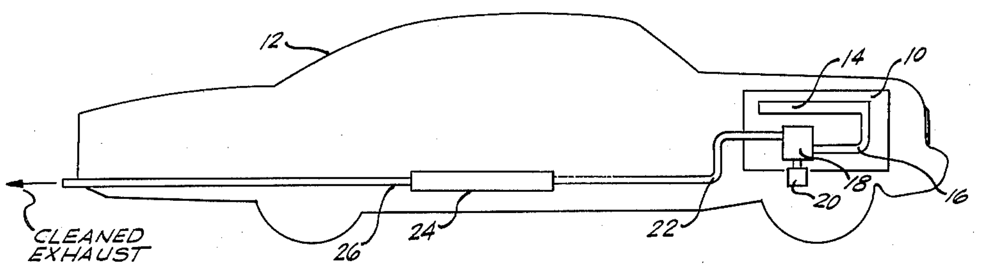

FIG. 1

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EXHAUST TREATMENT APPARATUS AND METHOD

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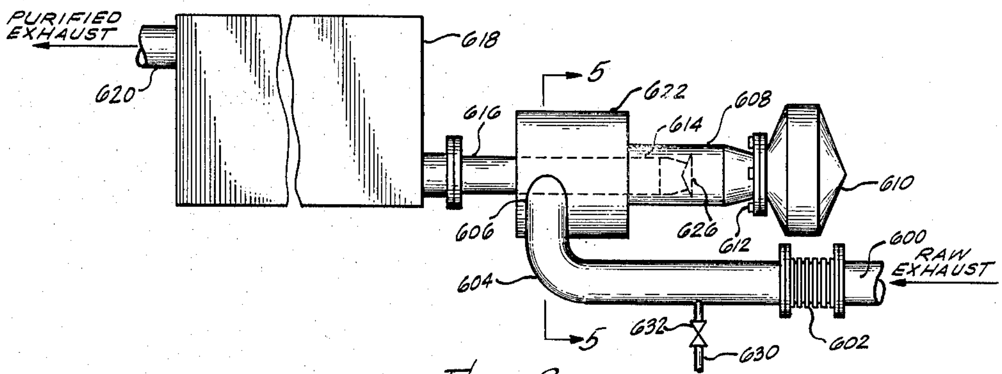

FIG. 2

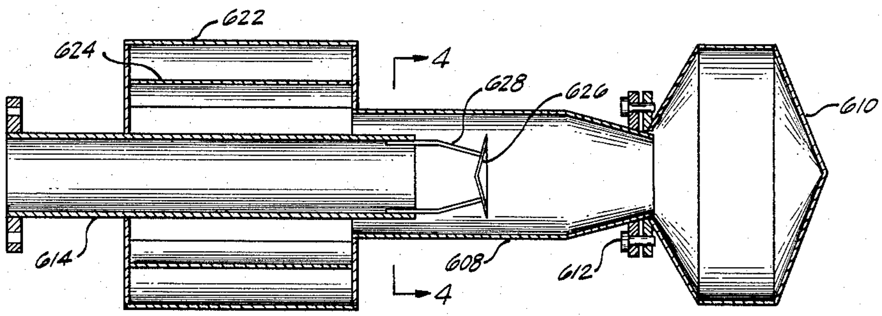

FIG. 3

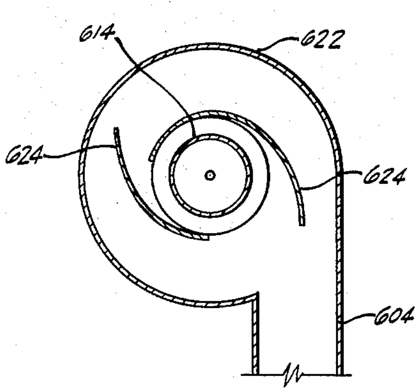

FIG. 5

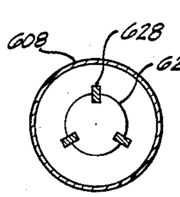

FIG. 4

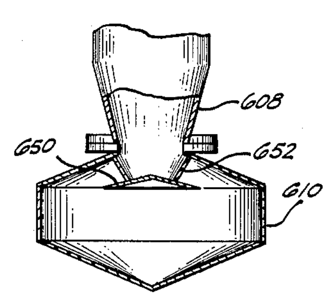

FIG. 6

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EXHAUST TREATMENT APPARATUS AND METHOD

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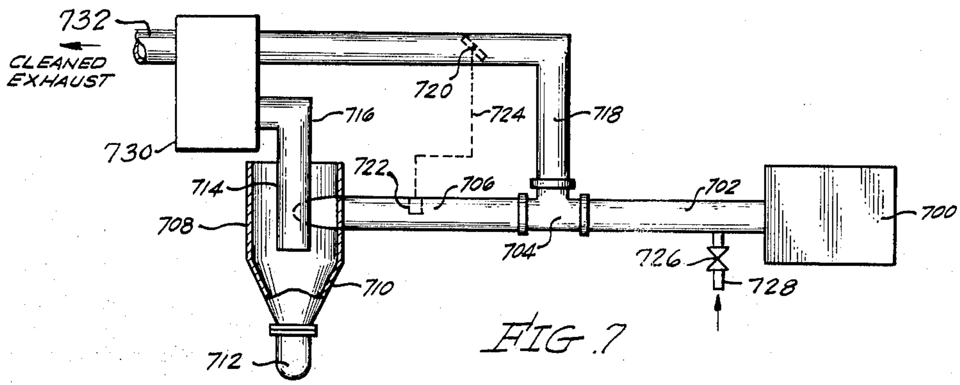

FIG. 7

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EXHAUST TREATMENT APPARATUS AND METHOD

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Filed Aug. 7, 1961, Ser. No. 129,760
The portion of the term of the patent subsequent to May 12, 1981, has been disclaimed
7 Claims. (Cl. 60—30)

This application is a continuation-in-part of application Serial No. 40,305 filed July 1, 1960, now matured as U.S. Patent No. 3,132,473.

This invention relates to the abatement of air pollution by the control of internal combustion engine emissions, and in particular concerns new and useful improvements in methods and apparatus for removing pollutant materials from the exhaust gases of automotive internal combustion engines burning metal-containing additive fuels.

The existence of noxious and harmful gaseous components, such as carbon monoxide, nitrogen oxides, sulfur oxides and hydrocarbons in the exhaust gases expelled from internal combustion engines powering automotive vehicles is well known. Many systems have been devised in the past in an attempt to remove these pollutants from the exhaust gas, but little attention has been given to eliminating the particulate metal compounds in these automotive exhaust streams which result from the passage of metal-containing gasoline and oil additives through an internal combustion engine. Tetraethyl and tetramethyl lead, used extensively as antiknock additives in most hydrocarbon automotive fuels, produce lead compounds in the exhaust which contribute to air pollution, and which have substantial value if they can be recovered. Tremendous quantities of lead are expelled every day in the combustion of lead-containing fuels, e.g., in the Los Angeles Basin of Southern California alone, in excess of about 30,000 pounds of lead is exhausted from vehicles which burn about 6,000,000 gallons of gasoline every day. The practical elimination of this particular source of contamination has been an unsolved problem over the years.

Tetraethyl lead has been used since 1923 to provide the improved antiknock quality required to keep pace with more efficient engines having high compression ratios. Virtually all automotive gasolines today contain tetraethyl or tetramethyl lead, or both, in concentrations up to about 4 milliliters per gallon (about 0.15 weight percent lead). Commercial antiknock fluids also usually contain ethylene dibromide and ethylene dichloride to scavenge engine combustion chambers by converting lead oxide to lead halides which have greater volatility at engine temperatures and can be expelled. The elimination of lead from engines as thus manifested by the discharge of particulate oxides and halides of lead. In fact, substantially all of the particulate matter in auto exhausts, on a weight basis, is composed of lead compounds. For the most part, these compounds do not remain suspended in the atmosphere, but fall upon the highways and accumulate.

Metal compounds in the exhaust stream have posed a further problem in previous attempts to use afterburners and catalytic devices for purifying engine exhausts. The metal compounds, particularly those containing lead, have been found to poison most catalysts seriously, thus rapidly deactivating catalytic converters and making their use costly and impractical. Even where the catalysts are not seriously poisoned by metals such as lead, they are gradually coated with an adhesive deposit of metal salts that eventually covers the surface of the catalysts

and reduces their effectiveness. These metal salts, usually lead salts, have also been found to interfere with the effective life of sound-attenuating mufflers and direct flame afterburners by adhering to the internals of those devices thus plugging the flow areas and increasing the pressure drop through the entire exhaust system.

It is accordingly an object of this invention to provide an improved method and apparatus for the abatement of atmospheric pollution resulting from the operation of internal combustion engines which burn fuels having metal-containing additives.

Another object is to provide an improved method and apparatus for effectively removing a major portion of the metal compounds particles from automotive exhausts, thus preventing the dispersal of these pollutants into the atmosphere and onto the earth's surface.

A further object of this invention is to provide an improved method and apparatus for preventing the poisoning of catalysts used to treat internal combustion engines exhausts by removing a substantial portion of the particulate metallic catalysts poisons from exhaust gas streams, thus substantially prolonging the life of such catalysts.

A still further object of this invention is to provide an improved method and apparatus for substantially eliminating the physical deposition of metallic compound particles within the internals of mufflers and afterburners used in conjunction with internal combustion engines burning metal additive fuels.

An additional object of this invention is to provide an improved method and apparatus for obtaining optimum particle removal by inertial separation with exhaust gas streams from internal combustion engines having widely varying flow quantities.

A still further object of this invention is to provide an improved method and apparatus for enhancing the agglomeration of particulate solids in the exhaust gas streams from internal combustion engines and for decreasing the gas viscosity substantially to optimize the removal of particulate masses from the gas stream.

Another object of this invention is to provide an improved method and apparatus for minimizing the entrainment of collected solids from a collection zone of an inertial separator because of the breathing effect inherent with the widely varying exhaust gas volumes of internal combustion engines.

A further object of this invention is to provide an improved method and apparatus for adding auxiliary combustion air to an exhaust gas stream prior to catalytic conversion.

Other and related objects will be apparent from the detailed description of the invention, and various advantages not specifically referred to herein will be apparent to those skilled in the art on employment of the invention in practice.

We have now found that the foregoing objects and their attendant advantages can be realized with a conventional internal combustion engine, such as is used in the propulsion of motor vehicles, by providing an inertial particle separator which removes the metal-containing particles from the exhaust stream by changing the flow direction of the particle-laden exhaust, thus providing a cleaned exhaust gas stream substantially reduced in metal-containing particles. After removal of a substantial proportion of these metal-containing particulate compounds from the exhaust gas stream, the latter can be exhausted to the atmosphere through a conventional muffler, or it can be subsequently passed through a catalytic converter or afterburner with reduced poisoning of the catalyst and substantial elimination of the usual coating and plugging of afterburners with these metal compounds.

This invention is particularly concerned with the use of an apparatus which depends primarily on the separation of suspended matter from the gas stream by changing the flow direction of the gas. Of these devices, conventionally called inertial separators, the most common are cyclones and baffle chambers. The cyclone separator, one of the most widely used of gas cleaning devices, generally consists of a main precipitating cylinder with a tangential gas inlet, an inverted cone attached to the base for the collection of particulate matter, and a central gas outlet. The main precipitating cylinder can have a diameter from less than one-inch to several feet, depending on the efficiency desired and the amount of gas which must be handled. In a conventional cyclone, the gas enters tangentially either from a horizontal duct or through directing vanes, then spirals downwardly through the annular space between the main precipitating cylinder and the central outlet tube into a cylindrical or conical chamber, turns upward and forms an inner spiral of gas which leaves through the central outlett tube. The solids particles impact on the walls of the separator, lose their momentum, and fall to the bottom of the conical chamber of the cyclone where they are periodically removed. Cyclones are particularly effective, i.e., above about 90 percent efficiency, in removing particles or agglomerates 5 microns and larger. However, cyclones can remove much smaller particles, even 1 micron size and below. The conventional cyclone design has become standard and tables of detailed dimensions are available from many sources.

Another type of centrifugal separator, also operative in my invention, is a mechanical centrifuge wherein the centrifugal force comes not from the motion of the gas alone, but the gas rotation is obtained by means of a fan. The blades of the fan are especially shaped to direct the separated dust into an annular slot leading to a collection hopper while the clean gas continues to the scroll.

The impingement separator, another species of the inertial separator, depends on the inertial deposition of particles as a gas passes through an obstruction. The shape of the obstruction can vary from that of simple baffles to complicated patterns which give maximum impaction efficiency with minimum pressure loss. In baffle chambers, the simplest type of impingement separators, the suspended matter is impacted in the direction of flow while the gas undergoes at least one flow reversal, thus separating the gas from the solid particles. The tortuous flow of the baffle chamber is obtained by zigzag blades or shaped obstacles placed in the gas stream. These devices are particularly suitable for removing particles larger than 20 microns.

A particular feature of my invention is the protection of exhaust conditioning devices by pretreatment of the exhaust stream with inertial separators. These exhaust conditioners are usually either mufflers (sound attenuators) or devices for removing gaseous contaminants from the exhaust stream. Since the gaseous contaminants of automobile exhaust gases are for the most part unburned or partially burned hydrocarbons, one of the most effective methods of reducing these contaminants lies in completing the combustion initiated in the engine, thereby converting these contaminants into carbon dioxide and water. This is the principle of "afterburners" which are of two main types: the catalytic converter and the direct flame afterburner. The principal difference between the catalytic converter and the direct flame afterburner is that, with a catalyst present, considerably lower temperatures suffice to oxidize the combustible contaminant material.

In a catalytic converter, exhaust gases, usually with sufficient added air for complete oxidation of the contaminants, are brought into intimate contact with a catalytic material. A sufficiently high temperature must be maintained to insure a continuous and complete oxidation of the contaminants to carbon dioxide and water. With both the catalytic converter and the direct flame afterburner, provisions are normally necessary for a controlled air supply. Although the invention is not limited to the use of any particular catalyst, a typical preferred oxidation catalyst comprises small pellets, e.g., $\frac{1}{32}$-inch to $\frac{1}{4}$-inch, of an activated oxide carrier such as activated alumina, silica, beryllia, thoria, magnesia, zirconia or mixtures thereof impregnated with catalytically active metals or the metal oxides, or mixtures thereof, of metals such as copper, molybdenum, tungsten, nickel, cobalt, vanadium, chromium, manganese, titanium, tantalum, and iron.

One of the more common types of oxidation catalyst comprises noble metals which include platinum, palladium, gold, silver, iridium, rhodium, ruthenium, osmium, etc. These noble metals, when used as catalysts, are often generally associated with a refractory metal oxide and particularly an oxide of a metal in the left-hand column of Groups III and IV of the Periodic Table including particularly the oxides of aluminum, titanium, zirconium, hafnium, thorium, etc. Sometimes two or more metal oxides can be included in the catalyst and in other cases activating components can also be included in the catalysts. These activating components generally are acidic and include halogens, particularly chlorine and fluorine, other mineral acids, organic acids, and the like, the acidic component or components usually being associated with the metal oxide and/or metal in the combined state. In general, the oxidation catalyst is usually present in an amount from about 2 to about 30 percent, based on an overall weight of the catalyst and its support.

Suitable reduction catalysts for use in catalytic converters, either alone or in combination with oxidation catalysts, include active metals of Group VIII of the Periodic Table and/or their oxides supported on activated alumina, e.g., nickel, copper, and the noble metals. A catalytic reduction zone usually precedes a catalytic oxidation zone in a two-stage series catalytic treatment of exhaust gas streams, but the catalysts in both catalytic zones can be the same with only a difference in reaction conditions. Any suitable oxidation or reduction catalyst can be used which is capable of operating over long periods of time at elevated temperatures, e.g., temperatures of 600° F. to 1,300° F. are common. However, the successful catalysts are all somewhat susceptible to metal poisoning or deactivation from lead, manganese, boron and the like. Although some catalysts appear to have a certain degree of lead tolerance, maximum catalyst life and efficiency can be attained only by the removal of metal poisons such as lead from exhaust gases prior to contacting the catalyst.

My invention will be more readily understood by reference to the accompanying drawings which form a part of this application.

FIGURE 1 is a schematic diagram of one of the simplest embodiments of this invention comprising an inertial separator and an exhaust conditioner as incorporated on an automobile.

FIGURE 2 is a plan view of a horizontally mounted cyclone separator attached to a catalytic converter with air addition to the raw exhaust gas prior to entry into the cyclone separator.

FIGURE 3 is a cross-sectional view of the cyclone separator of FIGURE 2 taken along the horizontal center line of said cyclone separator.

FIGURE 4 is a cross-sectional view taken along lines 4—4 of the baffle located at the entrance to the outlet pipe of the cyclone separator of FIGURE 2.

FIGURE 5 is a cross-sectional view taken along lines 5—5 of the upper portion of the cyclone separator illustrated in FIGURE 2.

FIGURE 6 is a reduced sectional view of the solids collector of FIGURE 2 with a baffle plate located within the solids collector opposite the opening into the cyclone.

FIGURE 7 is a schematic diagram of the apparatus of this invention illustrating a specific embodiment of an inertial separation device comprising a T-separator, a cyclone separator, and a butterfly control valve for optimizing flow through the cyclone separator.

It is to be understood that although the metal-containing particle removal method and apparatus of this invention is particularly applicable to the internal combustion engines used in automotive vehicles, it is also broadly useful for other combustion engines such as those used in stationary installations, airplanes, and the like which use metal-containing fuels and oils.

Referring now more particularly to FIGURE 1, the apparatus there shown consists essentially of a particular exhaust gas system for internal combustion engine **10** used to power automotive vehicle **12** by burning metal-containing fuels. The particle laden exhaust gas from internal combustion engine **10**, running at normal load, is expelled at a temperature of about 1,000–1,600° F. through exhaust manifold **14** into exhaust conduit **16**. Exhaust conduit **16** conveys the exhaust gas to inertial separator **18** at a flow quantity between about 6 s.c.f./minute and about 250 s.c.f./minute (s.c.f.=cubic feet at 60° F. and one atmosphere pressure) and at a temperature usually between about 500° F. and about 1,200° F. Inertial separator **18**, wherein there is some form of directional flow change of the exhaust gas stream, can be located at any point in the exhaust system after exhaust manifold **14**, but for convenience of access is preferably located near internal combustion engine **10** in the engine compartment. Solids particles, comprising primarily the oxides and halides of metals in the fuels, are separated from the exhaust gas stream and collected in solids container **20**. Periodically, container 20 is emptied of accumulated metal compound solids. The cleaned exhaust gas stream exits from inertial separator **18** via conduit **22** which conveys the cleaned exhaust gas stream to exhaust conditioner **24**. Exhaust conditioner **24** can be a direct flame afterburner, a catalytic converter, a conventional sound attenuating exhaust muffler, or some other type of exhaust conditioner. After treatment in exhaust conditioner **24**, the exhaust gas stream is expelled to the atmosphere via tail pipe **26** whose outlet is conventionally, but not necessarily, located at the rear of the vehicle.

Conduits **16**, **22** and **26** are usually constructed of 1½ to 2-inch I.D. steel tubing, such as is conventional for exhaust system piping, but any tubing size can be used to give appropriate flow velocities and pressure drops. The overall pressure drop of the exhaust system shown in FIGURE 1 is usually about 2 to about 10 inches of water at cruising speed (about 50 m.p.h.), but can vary from less than one inch of water to more than 15 inches of water with ordinary passenger vehicles. The representation in FIGURE 1 is illustrative of an exhaust system having a single common exhaust line, but it is common in modern internal combustion engines, particularly those with eight cylinders, to have dual exhaust system conducting the exhaust gases from each side of the engine to separate exhaust gas systems. In such a case, the system as shown in FIGURE 1 would be duplicated for each side with appropriate sizing to accommodate the reduced exhaust gas flow. The method and apparatus of my invention has been successfully applied to engines on vehicles having dual exhaust systems and any number of inertial separators can be integrated into an exhaust system.

Referring now more particularly to FIGURES 2, 3, 4 and 5, the apparatus there shown comprises an embodiment of my exhaust treatment system. The exhaust gases, from an internal combustion engine (not shown) using a leaded gasoline, are conducted through horizontally mounted cyclone separator vessel **608** via raw exhaust conduit **600**, expansion joint **602**, and second exhaust conduit **604**. The dirty exhaust gas stream in conduit **604** is tangentially introduced into cylindrical cyclone separator vessel **608** via tangential entry **606** in housing **622**.

The gases are accelerated to the interior surface of outer wall of vessel **608** and directed through the annulus between tube **614** and vessel **608** by two involute vanes **624** (see FIGURES 3 and 5) forming an outer vortex spiraling towards solids collector **610**. At the same time, an inner vortex is formed between the entrance of central gas outlet tube **614** and solids collector **610** which, although spiraling in the same radial direction as the outer vortex, passes out the central gas outlet tube **614**. Because of the law of conservation of momentum, the angular velocity of the inner vortex is greater than that of the outer vortex. This difference in angular velocity creates the centrifugal driving force necessary to force the lead particles towards the wall of cylindrical cyclone separator vessel **608**. Thus, because of the high centrifugal acceleration imparted to the lead particles, the cyclone operates as effectively in the horizontal position as when the longitudinal axis of the cyclone is in a vertical or intermediate angular position.

As illustrated in the underneath plan view of FIGURE 2, it is often convenient to install the cyclone and catalytic converter horizontally under a vehicle. The solid particles are concentrated by centrifugal action at the periphery of cyclone vessel **608** where they impact with the vessel walls and are carried along the vessel walls toward solids collector **610**. The swirling outer gas vortex within cyclone separator **608** carry the solids into solids collector **610** where they are collected for eventual recovery. The metal compound particles are periodically recovered from solids collector **610** by removing bolts **612**. Solids collector **610** can of course be made removable by any other suitable conventional attachment means. Exhaust gas spiralling between the walls of cyclone separator vessel **608** and central gas outlet tube **614** pass to the opening in central gas outlet tube **614** where the exhaust gas, now substantially free of solid particles, flows into central gas outlet tube **614** which is connected directly to cleaned exhaust gas conduit **616**. The cleaned exhaust gas is then conducted to catalytic converter **618** via exhaust gas conduit **616**. In catalytic converter **618**, the substantially particle free exhaust gas from exhaust conduit **616** is treated at about 1,000° F. with an oxidation catalyst, comprising 10 percent copper oxide by weight on a silica-stabilized alumina support, for the removal of hydrocarbons and other combustible materials. The purified exhaust gas, substantially contaminant free, is then expelled from catalytic converter **618** to the atmosphere via tail pipe **620**.

Excessive turbulence can occur in solids collector **610**, particularly during wide open throttle acceleration of the internal combustion engine source of the raw exhaust gas in conduit **600**. The lead particles in solids collector **610** are in a continuous swirling motion because of the vortex action of the cyclone. Unless these solids are directed to a quiescent zone, they tend to become entrained and carried out central outlet tube **614**. This type of entrainment is most serious during periods of high turbulence such as on wide open acceleration of the internal combustion engine source. A further embodiment of this invention then entails the connection of a second solids collector to the peripheral wall of the cyclone collection section so as to provide a dead zone free of turbulence. The cyclone solids collector, such as **610**, is connected to a retainer pot by means of an orifice, slot, or pick-up vane so as to skim the solids from the swirling vortex.

A further phenomenon inherent in the use of cyclone separators for removing solids from widely varying exhaust gas quantities, is a breathing effect which occurs from compressing the gases in the cyclone during acceleration and expanding the gases during deceleration. This "breathing" in the cyclone tends to carry out some of the collected fine particles by entrainment. Deflector plate or baffle **626**, held by brackets **628** to the bottom of central outlet tube **614**, deflects entrained particles to the outer whirling vortex of gas where they are returned to solids collector 610. The cone of deflector plate 626 can be oriented as shown in the drawing with the point of the cone adjacent the entrance to central outlet tube 614 or, deflector plate 626 can be reversed so that the cone of deflector plate 626 slopes in the same general direction. Baffle 626 can be of any suitable diameter or shape such as a horizontal plate, but preferably is a cone of a diameter slightly less than that of the opening of central outlet tube 614, and preferably about 70 to 80 percent of the diameter of central outlet tube 614. The spacing of cone deflector 626 from the entrance to central outlet tube 614 should be less than about a distance equal to the diameter of central outlet tube 614, and preferably about 75 percent of the central outlet tube 614 diameter. However, the diameter of cone 626 and its spacing from central outlet tube 614 can be greater or lesser without substantially changing the beneficial effect of cone deflector 626.

A further modification utilizing a baffle similar to cone deflector 626 is shown in FIGURE 6. In this embodiment, a deflector plate 650 is suspended within solids collector 610 by means of brackets 652 and is usually spaced from the opening into cyclone vessel 608 by a distance equal to or less than the opening diameter, and preferably a distance equal to about 75 percent of the opening diameter. Baffle 650 usually has a maximum diameter less than the diameter of the opening, and preferably a diameter equal to about 70 percent of the opening diameter. Deflector plate 650 thus has substantially the same configuration and characteristics as deflector plate 626 previously discussed in relation with the central outlet tube 614 within cyclone vessel 608.

Since cyclonic separators operate more efficiently at lower gas temperatures, advantage can be taken of the cooling effect from mixing auxiliary air with the raw exhaust gas prior to entry into the cyclone, particularly where such air is required for reaction in a catalytic converter located subsequent to a cyclone. As shown in FIGURE 2, auxiliary air can enter via conduit 630 at a rate controlled by valve 632. In addition to the advantage of the lower viscosity which is inherent with the lower temperature gas streams resulting from the mixing of auxiliary air with the raw exhaust, a further advantage to adding cooling air relates to the greater agglomerating characteristics of the solids at lower temperatures. The solid metal particles in the cooler exhaust entering cyclone separator 608 agglomerate more readily, thus giving the solids a greater tendency to separate in the cyclone because of greater particle mass. This auxiliary air can be supplied to air conduit 630 by a conventional venturi aspirator or by a pump, or other means. A preferable system comprises a variable flow pump controlled proportionally with engine speed to provide the desired exhaust gas-air ratio.

Other cooling means can also be used with the auxiliary air, or in place of auxiliary air, such as placing cooling fins on the exhaust header and piping prior to the cyclone separator, directing air flow over the exhaust piping and other heat exchange techniques such as the use of indirect liquid coolant or the injection of water into the raw hot exhaust gas stream. Usually the cyclone and exhaust lines leading to the cyclone are left bare and uninsulated to take advantage of the higher cyclone efficiencies at lower temperatures. However, although there is a tendency for the particles to agglomerate at lower temperatures and thus become easier to separate, a cyclone can operate successfully at any temperature as long as the gas velocities are suitable.

Cooling means other than adding air to the exhaust gas stream is particularly useful where the cleaned gas from the cyclonic separator goes first to a reducing reaction in a catalytic converter since oxygen in excess of that normally present in exhaust gases is detrimental to such a system. The lower limit of cooling of the exhaust gases in any case is usually controlled by the threshold activity

temperature of the catalyst, i.e., the temperature at which catalyst first shows a detectable catalytic activity.

Another specific embodiment of the apparatus of this invention is shown in FIGURE 7. Exhaust conduit 702 conducts expelled raw exhaust gases from internal combustion engine 700 which is burning a leaded gasoline to T-separator 704 wherein the particle laden exhaust gas is separated into a cleaned stream (reduced particulate content) which is exhausted through valved conduit 718 controlled by volume control valve 720, and a dirty stream (increased particulate content) which is passed to cyclonic separator 708 through conduit 706. In conduit 706, pressure responsive means such as spring loaded diaphragm-piston element 722 is positioned to sense any pressure change in conduit 706. Mechanical linkage 724 interconnects butterfly control valve 720 and pressure responsive element 722.

The T-separator is preferably at 90° as shown but can be aligned at other angles, usually between 15° and 165°. The lead compound particles, having a much greater inertia than the gaseous components, tend to continue in the original direction of flow in conduit 702 as they pass through T-separator 704 and thus are carried via conduit 706 into cyclonic separator 708. However, a portion of the gas stream, which makes the flow direction change and flows upward via conduit 718 at a rate controlled by butterfly control valve 720, is exhausted from the extremity of conduit 718 as a cleaned stream of substantially reduced lead content into catalytic converter 730. The dirty gas stream enters cyclonic separator 708 via conduit 706. In cyclone separator 708 the gas velocity generates a centrifugal force which impacts metal-containing solids particles against the walls of the cyclone separator 708 and the particles settle downwardly into the collector 712. The gas stream passes downward from the tangential entry of the cyclonic separator towards the inlet of central exit conduit 714 of cyclonic separator 708. The lead compound particles are swirled into the lower portion of cyclonic separator 708 and are collected in particle collector 712 which is removably attached to cyclonic separator 708. The exhaust gas, after undergoing a change of flow direction in cyclone 708, is withdrawn via central exit conduit 714 to conduit 716 which conducts the substantially particle-free gas stream from cyclone separator 708 into catalytic converter 730, for the removal of obnoxious and harmful components, producing as an effluent purified exhaust gas which is removed from the catalytic converter 730 via tail pipe 732. Auxiliary air necessary for the combustion of hydrocarbons, carbon monoxide, and other obnoxious components in the catalytic converter 730 can be added at several locations. In FIGURE 7, auxiliary air is added to the raw exhaust in conduit 702 via conduit 728 at a rate controlled by valve 726 to take advantage of the cooling effect which can be gained by mixing raw exhaust gases with the auxiliary air.

The cleaned exhaust gas stream in conduit 718 is regulated by butterfly control valve 720 which is used to maintain a substantially constant volume of dirty exhaust gas flowing through conduit 706 (therefore constant pressure drop), thus assuring substantially optimum operation of cyclonic separator 708. Control valve 720 can be controlled hydraulically or mechanically, or by other suitable means to open or close with fluctuations in pressure or flow quantity in line 702 or line 706 or also with manifold vacuum variation. Mechanically biasing of valve 720 can also be done with a spring, or other suitable means responsive to changes in exhaust gas volume or pressure through conduits 702 or 706. A typical device for automatically regulating the flow of a gaseous fluid by means of the intake manifold pressure is illustrated in U.S. Patent No. 2,880,079. With a substantially constant pressure drop across cyclonic separator 708, the design of cyclone 708 can be set at an optimum for particle removal from the exhaust of a particular engine. Thus, as the exhaust gas flow in line 706 decreases, the pressure decreases and pressure responsive element 722 reacts via mechanical linkage 724 and butterfly control valve 720 closes to maintain a substantially constant flow to cyclonic separator 708. As the exhaust gas flow in line 706 increases, the pressure increases and valve 720 opens sufficiently to maintain a substantially constant exhaust gas flow to cyclonic separator 708.

Any metal-containing particle can be removed by the method and apparatus of the invention. For example, if a gasoline additive contains other metals, such as boron, manganese, phosphorous and the like, then the oxides, halides, and similar compounds of these metals removed from the exhaust stream by the inertial separator. Although the major portion of the metallic solids in the exhaust gas is derived from metal-containing fuel additives such as lead and manganese, a portion of the metal also comes from the metal additives used in compounding lubricating oils. Lubricating oil is constantly being burned in the combustion chamber of an internal combustion engine, and the combustion products, including some metal compounds, are exhausted with the fuel combustion products. Some of the metals commonly found in lubricating oils, such as phosphorous, zinc, boron, potassium, and the like, are known catalyst poisons and their removal from the exhaust stream is advantageous for the same reasons previously discussed with respect to lead. Another source of metal compound particles in the exhaust gas stream is the corrosion which takes place within the engine interior and exhaust manifold. This corrosion produces iron oxides and salts as well as oxides and salts of alloying elements, all of which are advantageously removed from exhaust gases prior to catalytic treatment.

A cyclonic separator installed on the exhaust outlet of an internal combustion engine behaves like an orifice and exhibits a pressure drop which increases with the square of the gas velocity. This pressure drop is the so-called back-pressure on the engine combustion chamber. Cyclones operate more efficiently at higher pressure drops, but any added back-pressure on the engine exhaust outlet results in a power loss. Consequently, the ultimate cyclone design in my invention is a compromise between engine performance and cyclone efficiency. As a design basis, the cyclone pressure drop is usually set at a value no greater than that of a standard muffler. The normal pressure drop in the conventional exhaust systems of automotive vehicles is in the range of 2 to 10 inches of water. Cyclones are least efficient at low speeds and idle and most efficient at high speeds and during acceleration. However, these characteristics are not necessarily disadvantageous since it is during periods of high power output that most of the lead is exhausted from internal combustion engines.

The apparatus of this invention, and in particular the inertial separators, can be installed in any combination of number and sizes desired to obtain a particular pressure drop. Thus, cyclones, T separators, and the like can be installed in series or in parallel to provide any desired particle separation efficiency and pressure drop. If it is desired to take a greater pressure drop in the exhaust gas system than the conventional 2 to 10 inches of water, then some type of flow booster such as a fan, pump, aspirator or the like can be incorporated into the exhaust system to provide the necessary energy to overcome the additional pressure drop through the exhaust system.

A cyclone of a design similar to that shown in FIGURE 2 and capable of handling the full exhaust load from a 352 cubic inch displacement internal combustion engine has an outer cyclone vessel diameter of about 4 inches. An alternative system uses two cyclones in parallel of the same design as that of FIGURE 2 each having a 2¾-inch outer vessel diameter and each about 19 inches in length. These cyclones normally remove from about 60 to about 80 weight percent of the exhausted lead compounds (about 0.2 pound per 1,000 miles) averaged over a wide variety of engine loadings. A catalytic converter attached to the outlet of such cyclonic separators has its life extended by a factor of at least 3 to 5. A further alternative design comprises adding cyclones to the exhaust gas path as the speed is increased by means of flow control valves, pressure control valves, or the like responsive to total exhaust gas flow or pressure, e.g., multiple cyclones in parallel with a variable selection of cyclone multiples. Thus, such a system comprises flow control valves which control the exposure of a multiplicity of cyclones in a manner which is responsive to the total exhaust gas flow or the total pressure drop across the cyclone system or some other suitable conventional control means responsive to the overall flow conditions which are optimum for cyclonic separation. An example of this type of device is a tube sheet with a plurality of small efficient cyclones mounted thereon which are exposed to flow proportionately with an increase in exhaust volume. A further example is a separation system where at low speeds a single cyclone handles the total exhaust. As the speed is increased, a second cyclone is exposed in parallel to the first cyclone to handle additional gas flow. As the speed increased further, a third cyclone is put in parallel to the first two cyclones, thus permitting each cyclone to operate only in its most efficient range. Therefore, the broad concept herein entails reducing the back-pressure on the engine under high loading by automatically making additional gas paths available as exhaust volume increases. This technique maintains a substantially constant low back-pressure with varying exhaust volumes and a substantially constant pressure drop across the cyclonic separator with varying exhaust volumes. This same concept, of course, applies to any other form of inertial separator as well as to cyclones.

Various other changes and modifications of this invention are apparent from the description of this invention and further modifications will be obvious to those skilled in the art. Such modifications and changes are intended to be included within the scope of this invention as defined by the following claims.

I claim:

1. In combination with an internal combustion engine; inertial separator means for removing solid particles from the exhaust gases of said engine;
a first exhaust gas conduit for delivering exhaust gas from said engine to said inertial separator means;
a bypass conduit branching from said first exhaust gas conduit at an intermediate location along its length, the axis of said bypass conduit intersecting the axis of said first exhaust gas conduit at an angle between about 15° and about 165°;
solid particle collecting means communicating with the interior of said inertial separator means and being adapted to receive therefrom solid particles separated from said exhaust gas passing through said inertial separator means;
solids removal means for removing collected solid particles from said solid particles collecting means;
clean gas discharge means for discharging a cleaned gas from said inertial separator means; and
air introduction means for adding air to said exhaust gas flowing within said first exhaust gas conduit, said air introduction means communicating with said first exhaust gas conduit intermediate between said engine and said bypass conduit branch.

2. A combination as defined by claim 1 including valve means within said bypass conduit for controlling the flow of exhaust gas through said bypass conduit, and in further combination therewith valve control means connected to said valve means for opening and closing said valve means in direct response to the pressure of the exhaust gas flowing through said first exhaust gas conduit.

3. In combination with an internal combustion engine: an inertial separator; a first conduit receiving said engine exhaust gas at one end and communicating at its other end with said inertial separator; air introduction means for adding air to said exhaust gas flowing within said first conduit; an exhaust gas bypass conduit communicating with said first conduit, the axis of said bypass conduit intersecting the axis of said first conduit at an angle between about 15° and about 165°; valve means within said bypass conduit for controlling the flow of exhaust gas through said bypass conduit; valve control means for opening and closing said valve means in direct response to the pressure of the exhaust gas flowing through said exhaust gas conduit means; solid particle collecting means communicating with the interior of said inertial separator and being adapted to receive therefrom solid particles separated from said exhaust gas passing through said inertial separator; solids removal means for removing collected solid particles from said solid particle collecting means; and means for discharging a cleaned gas from said inertial separator.

4. A combination as defined by claim 3 including: a cleaned exhaust gas manifold conduit communicating with said exhaust gas bypass conduit and with said means for discharging a cleaned gas from said inertial separator; a catalytic converter communicating with said cleaned exhaust gas manifold conduit and adapted to receive cleaned gas therefrom; and means for discharging purified exhaust gas from said catalytic converter.

5. A method of separating metal compound particles from the hot exhaust gas of an internal combustion engine burning a metal-containing fuel which comprises: passing said hot exhaust gas from said internal combustion engine into a main exhaust conduit; adding air to said hot raw exhaust gas flowing in said main exhaust conduit to cool said exhaust gas; diverting a first portion of said cooled exhaust gas at an angle from said main exhaust conduit thereby disengaging metal compound particles by inertia from said diverted gas portion and effecting a concentration of metal compound particles in the remaining undiverted gases flowing through said main exhaust conduit; abruptly changing the direction of flow of said remaining gases in a confined separation zone whereby metal compound particles are disengaged therefrom by inertia; collecting the disengaged particles in a collection zone away from the redirected flow of exhaust gas; and removing from said separation zone a second cleaned exhaust gas stream with a substantially reduced metal compound particles content.

6. A method as defined in claim 5 wherein said diverted gas stream and said second exhaust gas stream are combined, and the combined cleaned gas streams are passed through a catalytic converter to purify said cleaned exhaust gas.

7. The method of claim 5 including the step of maintaining the pressure drop across said confined separation zone at a value not to exceed a predetermined maximum by diverting varying portions of the flow as said diverted gas portion.

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