Nov. 5, 1963 L. L. JOHNSON ET AL 3,109,715

CATALYTIC AFTERBURNER

Filed Aug. 1, 1960 2 Sheets-Sheet 1

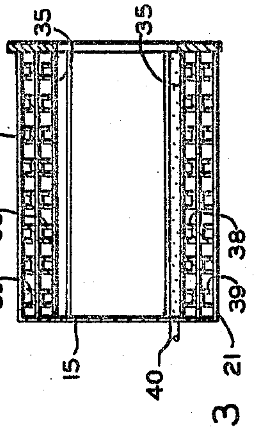

FIG. 3

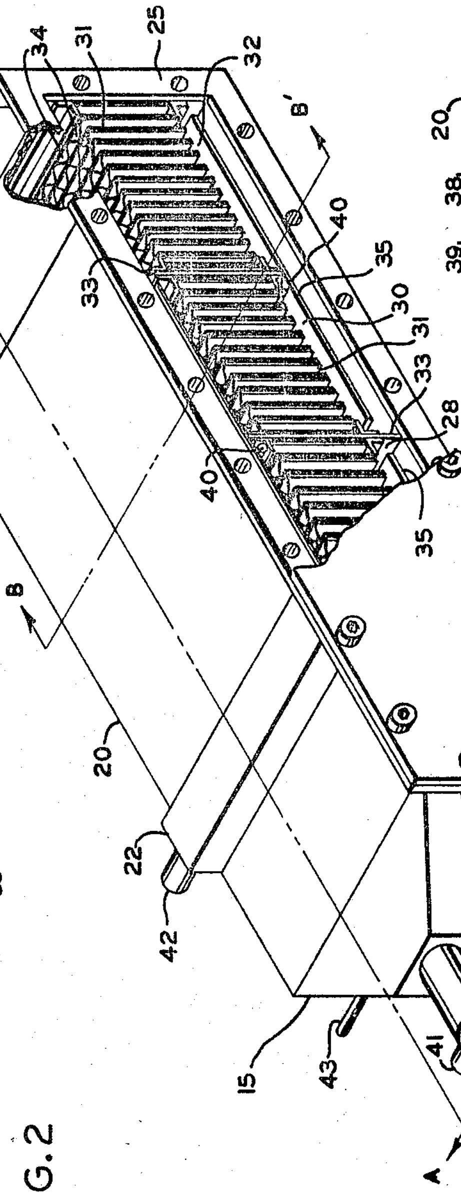

FIG. 1

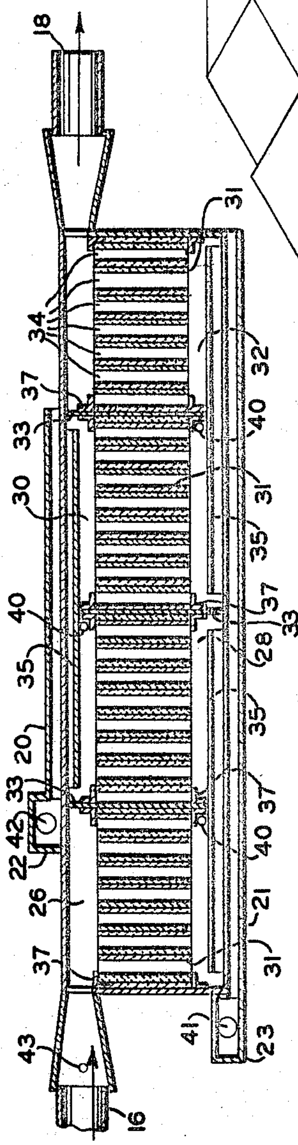

FIG. 2

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Nov. 5, 1963 L. L. JOHNSON ET AL **3,109,715**

CATALYTIC AFTERBURNER

Filed Aug. 1, 1960 2 Sheets-Sheet 2

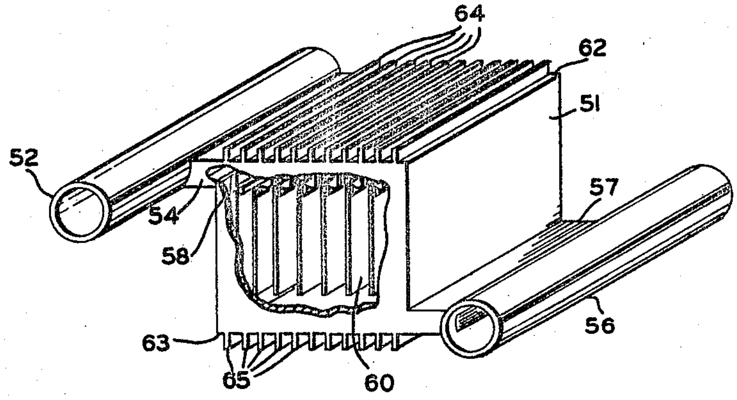

FIG. 5

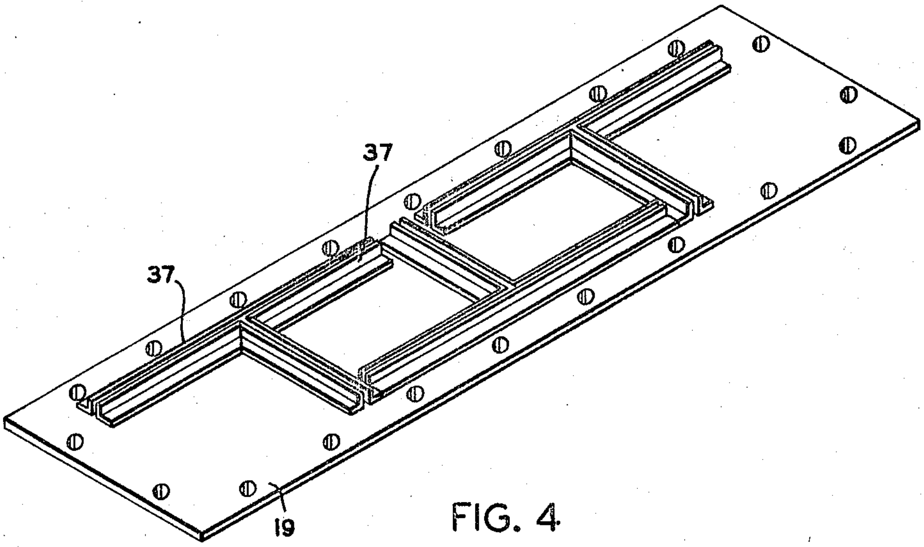

FIG. 4

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3,109,715
CATALYTIC AFTERBURNER

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2 Claims. (Cl. 23—288)

This invention relates to the catalytic oxidation of exhaust gases, and more particularly to a method for the catalytic oxidation of the exhaust gases from an internal combustion engine of an automobile by means of an afterburner, and especially to a catalytic afterburner embodying that method.

The problems in the development of methods for the catalytic oxidation of exhaust gases have been examined almost since the invention of the automobile. The art is replete with devices for this purpose, although none appears yet to have achieved acceptance by the public or by automotive engineers. The desirability of somehow destroying the noxious character of exhaust gases has been accentuated more recently by the recognition of the hazards to health engendered by the noxious products, particularly the so-called hydrocarbons which may actually include many varieties of chemical products of incomplete combustion, such as alcohols, aldehydes, ketones, organic acids and the like, as well as true hydrocarbons. Although carbon monoxide which is toxic may be present in exhaust gases from internal combustion engines in amounts from a fraction of a percent (by volume) to 10% by volume or even more, the so-called hydrocarbons are present in amounts up to about 0.1% (1000 parts per million) under cruise conditions, but may greatly exceed this during idling and deceleration. Since these latter conditions constitute a greater portion of an automobile's operation under city-traffic conditions, larger amounts of the hydrocarbons occur in exhaust gases in city areas and are believed to be a very significant factor in the production of "smog" conditions. As hereinafter described, the concentrations of hydrocarbons in actual practice are measured by methods which are not absolute and these figures refer to "parts by million as hexane" as determined by the methods hereinafter indicated.

The term "exhaust" as used herein will be understood to include any waste vapors from an internal combustion engine using hydrocarbon fuel; for example, the ordinary automobile engine. The term thus embraces not only the combustion products produced in the cylinders and expelled by concerted action of the valves and pistons, but also vapors formed from the action of the hot cylinder walls on the lubricating oil, either drawn into the cylinders and expelled or present over the oil sump in the crankcase. There is reason now to believe that the vapors and oil-mist from the crankcase oil are responsible for a significant fraction of the total hydrocarbon content of the exhaust of the car and injection of these vapors into the engine intake system through the carburetor as supplementary fuel and subsequent expulsion, as occasionally practiced now, is likely to become more common as increased efficiency is sought.

The exhaust of an automobile engine of even moderate displacement consists of large volumes of usually very hot gases, which are therefore rather difficult to manage. Ideally the exhaust should contain no waste fuel, but practically this is never achieved. The exhaust commonly includes entrained materials, particularly when fuel containing tetraethyl lead is employed. The expelled lead compounds are particularly troublesome as respects catalytic oxidation of exhaust gases since they may damage the catalyst, either by the accumulation of dust or, if excessively elevated temperatures exist for a short time, by glazing the catalytic surface. In addition, lead products may react with some catalysts at lower temperatures. In general it has been found that these disadvantageous effects are rapidly evident if at any point the temperature in the afterburner exceeds approximately 1200° F. That is not to say that a short time at 1250° F. or even 1300° F. will result in glazing, or inactivation by other mechanisms, but prolonged temperatures above about 1200° F. must be avoided, if a catalytic unit is to operate in a practical and successful manner.

As pointed out above, large volumes of exhaust gases are produced. The standard cubic foot is employed to designate the volume of gas measured at 70° F. and 1 atmosphere pressure. Since exhaust gases may vary in volume from about 5 to 300 standard cubic feet per minute, it will be evident that a very considerable velocity of gas must therefore be maintained through the exhaust system and that rather large ducts must be provided to avoid undue backpressures, which tend to reduce the efficiency of the engine.

It appears that it is not generally recognized in the descriptions of devices of the prior art that in the design of such accessories for automobiles there are very definite practical limitations as to what can be fitted into an automotive vehicle. Considerations of accessibility, for replacement of parts as well as size and shape, go far in determining the utility of such devices. Since it is common practice to provide that exhaust pipes follow the bottom of the car and pass between various members, the space available for an exhaust afterburner unit on a standard automobile is about that of a conventional muffler and should probably not greatly exceed the limits of dimensions and proportions of a muffler.

It is an object of this invention to provide a method for the catalytic oxidation of exhaust gases. A further object is to provide a compact catalytic exhaust afterburner in which oxidation is controlled so as not to exceed a gas temperature of about 1200° F. A further object of the invention is to provide an afterburner which also functions as a silencer. Other objects of the invention will become evident hereinafter.

In accordance with the above and other objects of the invention, it has been found that oxidation of hot exhaust gases containing carbon monoxide and hydrocarbons can be very advantageously effected by passing them through catalyst-impregnated or catalyst-surfaced honeycomb ceramic shapes in one, or two or more stages, and removing sufficient amounts of the sensible heat of the gases acquired by the gases from the reaction at or on the catalyst so that the temperature of the gases, though raised through oxidation, does not exceed about

1200° F. In general, a supplementary amount of air is supplied before the separate stages in such amounts that sufficient oxygen is present to assure oxidation of residual carbon monoxide and/or hydrocarbons without exceeding a temperature of about 1200° F. in each stage. This supplementary air is sometimes hereinafter referred to as secondary air. Preferably the passage of gases from one stage to another is accompanied by a change in their direction.

This process, in which the oxidation of the exhaust is separated into stages, in each of which a partial oxidation is accomplished as hereinafter described in more detail, is especially easily accomplished by the catalytic afterburner device of the invention. This device comprises an inlet plenum, a first catalyst chamber containing an oxidizing catalyst supported on a honeycombed ceramic (more fully described below), the passages of which are disposed at right angles to the flow of the inlet gases, an exit plenum from the first catalyst chamber which is connected with an inlet plenum for the second catalyst chamber, the flow of gases into these plenums being again at right angles to the flow of gases from the plenums referred to, thus requiring the exhaust gases to flow in a direction parallel and opposite to that in the first catalyst chamber and into an exit plenum connected with an inlet plenum for a third catalyst chamber, again so disposed as to require change in direction of gas flow; the third catalyst chamber likewise contains a catalyst support positioned to impose a change in direction of gas flow, now parallel and opposite to that in the second chamber, into an exit plenum connected with an inlet plenum for the last catalyst chamber, into which the gases flow at right angles to their direction on leaving the third catalyst support, and into the last catalyst chamber, the flow being at right angles to the flow in the plenums, through the catalyst supports, and into an exhaust outlet plenum and thence to the atmosphere. The outlet plenum from the first catalyst chamber and the inlet plenum for the second catalyst chamber are provided with a common heat exchanger means to cool the exhaust gases, and the outlet plenum from the second catalyst chamber and the inlet for the third catalyst chamber are likewise provided with a common heat exchanger means to cool the exhaust.

It is a particular advantage of the devices of the invention that they are reversible; i.e. the entire device can be turned end for end so that the exhaust gases flow through them in the opposite direction, without changing the operation of the device. This is useful because in operation, particularly when platinum is used as a catalyst, the temperature required for effective oxidation of the catalyst on the first catalyst units in the sequence tends to rise as a result of gradual inactivation of the catalyst, while that of the more rearwardly disposed units does not change. When this rise has become excessive, it is useful to reverse the apparatus end for end on the exhaust system of the engine, thus exposing the relatively fresh catalyst on what was the last unit in the sequence to the incoming exhaust stream.

Referring now to the accompanying figures,

FIGURE 1 is a view in perspective, partially broken away to show details, of a catalytic afterburner unit embodying the method of the invention.

FIGURE 2 is a view of the article shown in FIGURE 1, in cross-section along line A—A'.

FIGURE 3 is a view of the article of FIGURE 1 in cross-section along line B—B'.

FIGURE 4 is a view of the inner side of a cover plate for the muffler and afterburner shown in FIGURE 1. FIGURE 5 is a view in perspective with one side thereof broken away to show the interior detail, of a catalytic afterburner unit which is another embodiment of the invention.

Referring to FIGURE 1 there is shown an exhaust afterburner and muffler comprising a body shell 15 provided with an exhaust gas inlet 16 and outlet 18, and cover plate 19. Externally the shell is provided with heat exchangers 20 and 21, each of which is fitted with an inlet plenum 22 and 23 and an air inlet 42 and 41, all respectively. Arranged within the shell are several catalyst chambers 26, 28, 30 and 32, each of which contains a catalyst support consisting of a unitary block of ceramic 31 having many parallel, ordered passageways 34 of predetermined shape and size, and of relatively great length-diameter ratio. The chambers are formed by divider plates 33 and the sides, top and bottom of shell 15. Attached to the divider plates and extending from side to side of shell 15 are baffle plates 35. Perforated tubes 40 and 43 are provided for introduction of supplementary air upstream of the catalyst chambers as more fully described in connection with FIGURE 2.

The construction of the device is also apparent from FIGURE 2, wherein the arrangement of heat exchangers 20 and 21, divider plates 33 and baffles 35 is shown in cross-section. Angle retainers 37 are shown holding the catalyst blocks 31 in place in and sealing the catalyst chambers 26, 28, 30 and 32 against substantial leakage around the edges of the catalyst blocks. Perforated distribution tubes 40 provide for addition of supplementary air for combustion. In the drawing angle retainers 37 and distribution tubes 40 are shown as extending to the edges of the catalyst blocks 31, however, it will be apparent that these components are appropriately constructed so as to permit entry of the angle retainers 37 on cover plate 19 (FIG. 4).

Tube 43 is used for introducing supplementary air upstream from the first catalyst chamber. FIGURE 3 shows the construction of heat exchangers 20 and 21 in somewhat greater detail internally. Attached to the interior of shell 15 are fins 38, extending longitudinally inside the shell, and bridging the space between the baffle plates 35 and the shell wall. Longitudinally extending fins 39 fill the space in the heat exchanger between the outer sides of shell 15 and the outer walls of the heat exchangers. Each heat exchanger has an air inlet at its forward end, indicated respectively as 41 and 42, while the other end of each heat exchanger is open to permit free exit of cooling air. Means (not shown) are provided for a supply of cooling air through inlets 41 and 42. Tubes 40, which are perforated to permit passage of air and provide for even distribution thereof so as to assist in adequate mixing and extend substantially across the width of shell 15 in the catalyst chambers, are connected to a blower (not shown) for the purpose of providing additional air for combustion, as required.

Referring to FIGURE 4, cover plate 20 is shown in detail with respect to its interior side construction. Angle retainers 37 are shown positioned to engage the edges of baffle plates 35 and divider plates 33. The cover can be attached to shell 15 by means of machine screws, which engage tapped holes in the body flange 25 for ease in replacing the catalytic units if necessary or a permanent joint can be made using welded construction, etc.

The operation of the combined muffler and afterburner shown in FIGURES 1, 2, 3 and 4 is as follows:

Referring again to FIGURE 2, hot exhaust gases enter the afterburner unit at inlet 16 as shown by the arrow and mix with supplementary air entering through the tube 43. They pass through the first catalyst chamber 26 and catalyst block 31, being channeled through the passages 34 of the catalyst-impregnated or -surfaced ceramic honeycomb in a direction at right angles to their initial direction of flow. Oxidation occurs as an exothermic reaction in accordance with laws of chemical kinetics for the temperature conditions and composition of gas prevailing so that the gases after passing through the catalytic honeycomb 31 enter the plenum space defined by the walls of the shell and the baffle 35 at a higher temperature than their original temperature and approaching 1000° to 1200° F. Because of the baffle 35 they are prevented from entering the second catalyst chamber 28 directly, and are mixed with supplementary air entering tube 40 and forced into the interior portion of the first lower heat exchanger unit 20 where heat is lost to fins 38 and is dissipated to the atmosphere in the exterior portion of the heat exchanger after conduction to fins 39, cooling air being supplied through inlet 41.

The first lower heat exchanger unit will be seen to be externally continuous and coextensive with the shell 15. Internally of the shell 15, however, the unit is separated by the divider plate 33 between the second and third catalyst chambers. The outer wall of shell 15 separates the hot exhaust gases from the cooling air which is forced through the heat exchanger unit through the inlet 41 and the manifold 23 which distributes the air among the channels formed by the fins 39, which also perform the useful function of strengthening shell 15.

The exhaust gases after deflection through the lower heat exchanger and passage therethrough are forced by the baffle 35 to enter the plenum below the second catalyst-impregnated or -surfaced ceramic honeycomb 31. They are forced to change direction of flow in entering the plenum and again when they pass through the second catalyst chamber 28 and the passages 34 in catalyst unit 31, in which further oxidation occurs exothermically, in a direction opposite to that of their passage through the first catalytic block. The gases then enter the upper plenum of the second catalyst chamber, and are mixed with supplementary air entering tube 40 and pass around the baffle 35 and through the channels defined by the fins 38 between the baffle and the shell wall, in upper heat exchanger 20. Heat is absorbed from the gas stream by the fins 38 and the inner surface of the afterburner and transferred to the outer fins 39 of the upper heat exchanger and thence to the cooling air (provided as described above) admitted thereto through the inlet 42 and distributed by the manifold 22 to the channels formed by fins 39.

The exhaust gases after being thus cooled are deflected into the upper plenum of the third catalyst chamber 30 and are forced through the passages 34 of the third catalyst-impregnated or -surfaced ceramic honeycomb 31 in a direction opposite to the flow in the second catalyst chamber. Further exothermic oxidation may occur, depending on chemical kinetics and stoichiometry, and the exhaust stream then passes into the lower plenum of the third catalyst chamber where it is mixed with further supplementary air admitted through tube 40 and is directed by the baffle 35 and divider plate 33 into the internal channels of the second portion of the lower heat exchanger 21 defined by the baffle 35 and the shell 15 of the afterburner and the fins 38 associated with the catalyst chambers 30 and 32. Heat is again transferred from the exhaust gases to the cooling air as described above in connection with the first catalytic stage.

It will be noted that not as much cooling is required at this point and the already partially heated air from the first forward portion lower heat exchanger is adequate for the purpose. This is the case because the heat liberated in the first catalystic stage is likely to be due to the oxidation of carbon monoxide which occurs most readily, whereas in the subsequent stages oxidation of hydrocarbons occurs at a relatively slower rate and there is less danger of excessive heating of the exhaust gas during passage through those stages, hence less heat need be removed. A catalyst which effects simultaneous oxidation of carbon monoxide and hydrocarbons is desirable but does not have a profound effect on the cooling requirements since the greatest part of the heat is still liberated in the first stages.

The cooled exhaust gases then are deflected into the plenum of the fourth catalyst chamber 32. They pass through the passages 34 of the fourth catalyst-impregnated or -surfaced ceramic honeycomb 31 in a direction opposite to that of their flow in the third catalyst block and, depending on kinetics and stoichiometry, are further exothermically oxidized. After passing through the upper plenum of the last catalyst chamber, the now substantially fully oxidized gases are directed into the outlet 18 of the afterburner and thence to the atmospheres.

The cooling air for the heat exchangers is provided by a suitable compressor, pump or air scoop (not shown) and is apportioned between the lower heat exchanger and the upper heat exchanger. A thermostatically controlled valve, or other temperature-dependent means (not shown) can be used to control the air flow so as to prevent the temperature of the catalyst blocks 31 from exceeding about 1200° F.

Since at least under certain driving conditions, insufficient air is available for complete combustion of the average exhaust gas composition, particularly depending upon the condition of the motor, provision is made for supplementary air to the exhaust stream by way of distribution tubes 40. Since this air must be at a pressure in excess of that in the exhaust stream, a small pump is suitably coupled to the engine. Speed-controlled systems can be used to actuate valves which permit amounts of air which insure complete combustion of the exhaust gases to flow into the catalyst chambers.

The devious path through which the exhaust gases are forced appears to serve three purposes. It enables the provision of cooling means between stages, it minimizes tendency to clogging of passageways by particulate matter (as from leaded fuel) and it serves as an acoustic barrier so that the unit is an effective muffler. While the baffles 35 serve to increase the number of changes of direction imposed on the exhaust gases and to ensure a more uniform distribution of flow through the channels of the catalyst block and heat exchanger, these baffles are omitted when it is desired to make use of the direct radiation of heat from the catalyst surfaces to the heat exchanger, in a single stage unit as shown in FIGURE 5.

It will be understood that in the above description the device is adapted to be positioned with its long axis parallel to the frame of an automobile. The reference to "upper" and "lower" bear only upon the relative positions as shown in the figure and there is no reason why the unit may not be mounted in an automobile in any desired orientation. If other considerations warrant, it may be placed in other positions than at the conventional position for the muffler. Likewise it will be evident that a further series of such stages may be used if desired with different dimensions so that the several stages are not equal in volume as shown in the drawings. It will be necessary only to balance the design so that adequate cooling can be provided between stages.

As an illustrative example of the manner of practicing the invention an afterburner is constructed as in the figure so that the body exclusive of the end manifolds is 24 inches long and the overall width is 8½ inches and the height is 7 inches including a flange for attaching a side closure plate. The interior is constructed as shown in the drawings, brackets being provided at each stage for positioning catalytic units 3 inches high and about 8 by 6 inches in area. The cooling fins are one-half inch high and run for the lengths of the respective heat exchanger units.

The catalyst-impregnated or surfaced ceramic honeycomb units are prepared from 10 mil thick sheets of alumina prepared by casting and then drying a slip consisting of 28 percent vehicle and 74 percent solids. The vehicle is a mixture of ketone and ester solvents. Solids are 5% organic binder (polymer of octadecyl acrylate, acrylic acid, cyclohexyl acrylate and acrylonitrile) and 95% of a ceramic consisting of 96% alumina and 4% talc. A portion of the sheets are corrugated to possess 7 corrugations per inch by passage through corrugating rolls heated to about 200° F. A portion of the composition employed for producing the sheets is diluted to 67 percent solids with nitroethane to produce a slip having a rather creamy consistency which is employed as an adhesive. Alternate sheets of flat and corrugated form are cemented together by painting the slip on the ridges of the corrugate and then laying the pieces together to form a honeycomb structure. This is repeated to give green forms somewhat larger than the desired final shape. The green forms are fired at 1450° F. for ½ hour in an electric furnace to destroy the binder and sinter the particles together. The total cycle of heating to temperature and cooling requires 16 hours. The shapes shrink to a certain extent during firing. After cooling, they may be ground with an abrasive wheel to fit the afterburner, if necessary. They are then impregnated or surfaced with platinum. Probably only the surface coating of platinum is effective at the gas velocities encountered. Impregnation is effected by dipping the ceramic shapes into a solution of 100.5 grams of chloroplatinic acid hexahydrate and 93.5 grams of aluminum chloride hexahydrate in sufficient distilled water to give about 4.5 liters solution. The shapes are immersed for a half hour during which time the system is evacuated; then they are removed, shaken free of excess solution and air dried. They are then fired in an electric kiln heated to 600° C. over 2 hours, held for 1 hour and allowed to cool over about 12–15 hours.

Other ceramic materials can be used for producing ceramic structures of the type used herein as catalyst supports. Thus, for example, beryllia, zirconia, barium titanate, steatite, porcelain, magnesia, petalite and the like can be used in the method described. Similarly, other organic binders, such as cellulose acetate, polyvinylbutyral, polyvinyl chloride and the like can be employed with suitable organic solvents.

The amplitude of the corrugations (i.e. the elevation distance between the peak of a ridge and the lowermost portion of an adjacent groove is made to be at least as great as the thickness of film that is corrugated, which means that the elevation distance between the peak of a ridge on one side of a corrugated film and the peak of a ridge on the opposite side of the film is at least twice as great as the film itself. This is a minimum, however, and preferably uniform corrugations ranging from about 3 to 10 corrugations per inch are used, the height of the corrugations being about as great as their peak-to-peak distance.

The oxidizing catalysts employed on the surfaces of the catalyst supports described herein can be a metal such as palladium, platinum, nickel, silver and the like, which are deposited on the supports in the usual way employed for depositing these catalysts on ceramic substrates. Oxides such as vanadia, chromia, chromites, cobaltites, mixed copper oxides and the like can also be employed and are likewise deposited on or incorporated into the surfaces of the catalyst supports in known fashion.

The catalyst-impregnated ceramic shapes are then inserted in the afterburner unit.

A six-cylinder in-line Ford engine having 223 cubic inch displacement (1956 model) is arranged so that test conditions, e.g. revolutions per minute, can be determined and so that air can be introduced into the exhaust stream as needed, at the points shown at 40 and 43 in FIGURES 1 and 2. The engine is adjusted for optimum performance temporarily employing a conventional muffler on the exhaust line and using a commercial leaded gasoline (about 3 ml. tetraethyl lead per gallon). The

engine drives a 20 kilowatt D.C. generator which is connected to a 5 ohm resistor, cooled with air, to provide a load. The afterburner unit is arranged on the exhaust line with a bypass to the conventional muffler and provisions for measuring temperatures at the beginning and end of each catalytic stage and for removing gas samples before each stage and at the exhaust outlet (five positions). Analytical samples are taken to include supplementary air introduced up to that point in the exhaust line. The data obtained in the tests are designated by symbols as indicated in the following table.

In this and subsequent tables temperatures are expressed in Fahrenheit-degrees and volumes of supplementary air are expressed in standard cubic feet per minute (s.c.f.m.).

Table I.—Symbols

	Temp.	Analytical Sample	Supplementary Air
Exhaust from Engine	T_1	A_1	S_1.
After 1st Catalytic Stage	T_2	A_2	S_2.
After 1st lower heat exchanger	T_3		
After 2nd Catalytic stage	T_4	A_3	S_3.
After upper heat exchanger	T_5		
After 3rd Catalytic stage	T_6	A_4	S_4.
After 2nd lower heat exchanger	T_7		
After 4th Catalytic stage	T_8	A_5	

The engine is warmed up at about 1200–1500 r.p.m. (generator delivering 135 volts) to operating conditions (180° F. water temperature) using the conventional muffler and is then switched so that the exhaust gases pass through the afterburner. This speed of the engine corresponds to cruising at about 25 to 35 miles per hour. Exhaust gases are about 45 standard cubic feet per minute and contain 880 parts per million of hydrocarbons measured by infrared absorption spectrometry and calculated as n-hexane and 2% by volume of carbon monoxide. Analyses for hydrocarbons are made using a benzene-ethylene-acetylene-sensitized detector cell in a non-dispersive infrared unit and for CO_2, O_2 and CO by conventional gas analysis in an Orsat apparatus.

Air is supplied to the heat exchanger at 15 standard cubic feet per minute divided so that about ⅓ passes through the upper heat exchanger and two-thirds through the lower heat exchanger.

The engine is run under these conditions for about 75 hours (equivalent to 2700 miles of steady driving) without stopping or adjustments so that the condition of the engine tends to deteriorate with an increase in output of hydrocarbons and carbon monoxide. At irregular intervals (expressed hereinbelow as elapsed miles) measurements of the temperatures and analyses of exhaust mixtures at various points designated as above are recorded. Variations in amounts of supplementary air are made prior to these meausrements so that essentially stable conditions exist and the amounts of supplementary air are those prevailing at the recorded times. The results are summarized in the following tables.

Table II.—Afterburner Temperatures and Supplementary Air Supplied

Elasped Mileage	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	S_1	S_2	S_3	S_4
140	640	1,125	950	885	410	815	700	700	3.0	0	0	0
600	505	1,060	735	880	405	805	730	730	3.0	0	0	0
960	580	990	855	1,050	500	1,100	970	970	3.0	2.0	1.1	1.5
1,420	640	1,150	960	1,170	520	960	820	820	2.5	2.0	2.0	2.0
1,880	630	1,195	1,045	1,260	545	1,060	900	900	2.5	2.0	2.0	2.0
1,950	630	1,180	1,010	1,245	530	1,035	860	860	2.5	2.0	2.0	2.0
2,220	620	1,225	1,060	1,230	525	1,080	900	900	2.5	2.0	2.0	2.0
2,700	620	1,225	1,060	1,230	525	1,110	920	920	[1]	[1]	[1]	[1]

[1] Not recorded.

Table III.—Analyses [1]

Elapsed Miles	A₁				A₂				A₃				A₄				A₅			
	HC	CO_2	CO	O_2	HC	CO_2	CO	O_2	HC	CO_2	CO	O_2	HC	CO_2	CO	O_2	HC	CO_2	CO	O_2
140	390	9.6	2.8	3.8	325	14.8	0.2	0.2	295	10.4	0	6.2	135	------	------	------	135	------	------	------
600	310	6.6	2.2	8.6	100	10.4	0	6.2	110	11.4	0	5.4	100	------	------	------	95	------	------	------
960	335	7.2	2.0	3.4	115	------	------	------	125	------	------	------	125	------	------	------	115	13.6	0.2	0.6
1,420	510	8.9	4.5	3.6	525	------	------	------	130	------	------	------	185	------	------	------	150	13.0	0	3.2
1,880	625	7.8	6.0	3.8	600	13.0	3.7	0	245	14.4	0.6	0.8	195	13.4	0.6	2.4	120	13.4	0	2.8
1,950	600	------	------	------	575	------	------	------	220	------	------	------	200	------	------	------	120	------	------	------
2,220	600	7.3	5.2	4.0	575	12.2	4.2	0	250	14.5	0.8	0.4	250	13.2	0.8	2.4	130	13.7	0	2.4
2,700	800	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	110	------	------	------

[1] HC=parts per million of hydrocarbons, CO_2, CO and O_2 as percent by volume.

It will be understood that although these data are recorded as obtained using the apparatus described, such figures are not absolutely accurate. It is possible that some of the temperatures, for example, the values of T_2, are in error and in any event these will vary depending on the precise placement of the thermocouple. It is also possible that incomplete mixing of supplementary air before sampling may result in error in analyses. It will be noted that the dilution by supplementary air is not corrected for in analyses. However, taken as a whole these data show the operation of the afterburner in accordance with the method of the invention.

In another run of an afterburner of the invention the same engine is provided with a cam operating the throttle on a 2 minute cycle (½ r.p.m.). The cycle is proportioned as follows:

	Degrees
Acceleration	35
Cruise at 42 m.p.h.	145
Deceleration	60
Idle at 17 m.p.h.	120

The catalyst is prepared differently. First, the shapes are treated to provide a better surface for deposition of platinum. Solutions are prepared of 300 cc. concentrated ammonium hydroxide diluted with 2700 cc. of distilled water and another solution of 908 grams of aluminum nitrate nonahydrate in 3630 cc. of distilled water. Shapes are first washed in the dilute ammonia and then dried until there is only a faint odor and the surface is almost dry. They are then immersed in the second solution for a few minutes, shaken free from excess solution and air dried. Each piece is then heated at 950° F. This process is repeated twelve times and thereby deposits a coating of alumina which appears to accept platinum so that there is a better balance of properties for simultaneous oxidation of carbon monoxide and hydrocarbons. The shapes are then immersed in a solution of 28.9 grams of chloroplatinic acid hexahydrate in sufficient distilled water to bring to 1863 cc., shaken to remove excess and dried, and platinum deposited by heating to 1100° F.

Thermocouples are arranged to record temperatures at the following locations:

Exhaust from engine	T_1
Center of 1st catalyst bed	T_2
Gas entering 2nd catalyst bed	T_3
Center of 2nd catalyst bed	T_4
Gas entering 3rd catalyst bed	T_5
Center of 3rd catalyst bed	T_6
Gas entering 4th catalyst bed	T_7
Center of 4th catalyst bed	T_8

Supplementary air is added at the locations designated above. The engine is run under the above cycling conditions for a total of 3,684 miles with shut-downs as indicated in the following Table IV. The same leaded gasoline is used as previously. The time lag during cycling is such that only the average temperature is recorded. In each case after shut-down, warm-up for about 2–4 minutes results in spontaneous commencement of catalytic oxidation.

Analyses are run on samples bled out at the same five locations and are determined by continuously indicating instruments as follows:

Oxygen (percent)
Carbon monoxide (percent)
Hydrocarbons (p.p.m.)
Total combustibles (percent)

It will be recognized that the values are of relative significance but may not be absolutely accurate.

Because of the cyclical operation of the engine the composition of the exhaust varies almost continuously, and maxima and minima (determined usually over about two cycles) are recorded for each constituent. These are ascribed to the longer phases of the cycle, i.e. idler or cruise conditions, since time lags are such that the possible effects of the shorter phases, acceleration and deceleration, are not discernible. With the engine employed, it appears that minima in percent of oxygen and parts per million of hydrocarbons and maxima in percent of carbon monoxide and total combustibles occur during the cruising conditions and the reverse during idling conditions. In order to show variations from pass to pass of the afterburner during operation, Tables V and VI are constructed for idle and cruise conditions respectively, maximum and minimum recorded values be ascribed as noted above. Throughout the run, cooling air is supplied to the upper heat exchanger at 5 standard cubic feet per minute and to the lower unit at twice this rate. The pressure drop through the afterburner unit varies from about 2 inches of water at idling speed to about 9 to 10 inches of water under the cruising conditions. S_1 varies between about 2.2 and 2.5 standard cubic feet per minute throughout the run and S_2, S_3 and S_4 are each 0.5 standard cubic foot per minute for the first 1,000 miles and 0.75 standard cubic foot thereafter.

Table IV.—Afterburner Temperatures and Supplementary Air Supplied

Elapsed Mileage	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8
210 [a]	630	1,310	810	500	690	840	640	520
210 [b]	590	1,250	800	500	710	900	690	520
545	550	1,250	800	500	710	930	690	510
898	600	1,270	810	510	730	1,000	710	550
1,000 [c]	590	1,260	820	540	750	1,050	750	580
1,027	490	1,250	810	550	720	950	700	490
1,190	600	1,310	850	540	750	970	690	950
1,546	600	1,320	850	530	750	1,000	700	990
1,732	600	1,320	850	550	700	1,000	690	975
1,888	550	1,280	850	600	650	1,000	700	1,000
2,237 [d]	640	1,250	800	560	740	1,060	750	1,050
2,312 [e]	570	940	790	520	660	770	610	410
2,409	660	940	820	500	660	800	620	430
2,473	440	850	780	550	650	710	560	380
2,806	540	900	860	590	660	740	590	400
2,899	530	920	860	530	660	740	590	400
2,972	320	940	875	610	655	740	575	410
3,104	625	670	520	550	580	660	490	350
3,684	510	880	840	560	640	710	550	400

[a] After one shut down.
[b] After start of operation again.
[c] Just before shut down for oil change.
[d] Shut down.
[e] Warmed up in 2-3 minutes.

Table V.—Analyses Under Idling Conditions

Elapsed Mileage	A_1				A_2				A_3				A_4				A_5			
	O_2	CO	HC	TC	O_2	CO	HC	TC	O_2	CO	HC	TC	O_2	CO	HC	TC	O_2	CO	HC	TC
210 [a]	3.75	3.7	200	8.0	0.0	0.7	176	2.0	0.5	0.3	144	1.2	1.0	0.1	88	0.5	1.5	0.7	114	0.2
210 [b]	4.5	3.6	168	>10	0.25	1.35	102	2.3	0.75	0.7	160	1.1	1.9	0.25	72	0.4	1.25	0.7	96	0.1
545	4.0	3.6	192	>10	1.05	1.2	184	2.2	1.05	0.6	184	1.4	1.55	0.075	104	0.4	1.85	0.075	88	0.3
898	4.0	4.2	280	>10	1.5	2.3	275	3.0	1.5	1.5	240	2.3	.075	0.30	152	1.1	1.0	0.25	122	0.4
1,027 [c]	4.0	4.0	224	>10	0.5	1.65	208	2.5	0.5	1.0	192	1.8	1.25	0.15	88	0.4	1.75	0.25	80	0.3
1,190	4.25	4.25	240	>10	0.75	2.25	240	2.5	0.5	0.8	208	3.6	1.5	0.24	122	0.5	1.75	0.12	122	0.2
1,546	3.25	4.0	240	>10	0.0	2.0	240	2.8	0.5	1.4	208	2.5	1.0	0.20	122	0.6	1.5	0.1	122	0.3
1,732	3.25	4.5	256	>10	0.0	1.8	256	2.9	1.0	1.0	244	2.6	1.0	0.20	120	0.5	2.0	0.12	104	0.3
1,888	3.5	4.4	256	>10	0.5	2.0	244	3.0	1.0	1.0	144	2.6	1.75	0.5	104	0.7	2.0	0.25	80	0.2
2,237	3.6	4.5	264	>10	0.0	2.4	264	4.8	1.5	1.8	176	2.7	1.5	1.4	152	0.7	1.0	0.40	128	0.5
2,312 [d]	4.5	3.4	184	7.2	2.0	1.4	168	2.3	2.5	0.15	120	0.6	4.5	0.5	80	0.4	4.25	0.0	72	0.2
2,409	4.5	3.9	184	8.0	2.0	1.6	168	2.5	2.0	0.2	120	0.8	4.0	0.1	88	0.5	4.0	0.0	56	0.2
2,473	4.0	2.8	184	7.9	2.25	1.5	168	2.3	2.24	1.2	120	0.9	3.75	0.15	80	0.6	4.0	0.0	56	0.1
2,806	5.5	2.7	200	8.0	3.5	0.75	160	2.0	1.75	0.1	96	0.7	4.0	0.0	68	0.0	5.5	0.0	49	0.0
2,899	5.0	3.0	208	7.8	3.5	0.4	160	1.8	2.0	.05	96	0.0	4.5	0.0	68	0.0	5.5	0.0	40	0.0
2,972	4.4	3.5	208	7.6	2.5	0.5	168	0.6	2.3	0.1	112	0.0	3.0	0.0	80	0.0	3.5	0.0	72	0.0
3,104	7.8	1.2	120	2.4	7.5	1.5	144	1.8	6.7	0.6	88	0.1	8.6	0.1	64	0.0	9.2	0.05	60	0.0
3,684	7.0	3.3	228	>10	4.5	0.4	160	0.22	4.5	0.05	96	0.1	0.65	0.0	64	0.0	0.55	0.0	64	0.0

[a] After one shut down, and adjustments.
[b] After warming up.
[c] Started up after shut down for oil change.
[d] Started up again: 2–3 minutes warm up time.

Table VI.—Analyses—Cruising Conditions

Elapsed Mileage	A_1				A_2				A_3				A_4				A_5			
	O_2	CO	HC	TC	O_2	CO	HC	TC	O_2	CO	HC	TC	O_2	CO	HC	TC	O_2	CO	HC	TC
210 [a]	2.0	5.0	144	>10	0.0	2.2	144	3.5	0.0	1.4	128	2.1	0.5	0.6	80	1.4	0.5	0.7	96	0.8
210 [b]	3.0	6.2	96	>10	0.0	2.85	128	4.0	0.25	2.0	96	2.7	1.25	1.20	56	1.2	0.25	1.85	80	0.7
545	2.5	5.7	128	>10	0.8	2.6	128	3.7	0.8	1.9	128	2.8	1.1	0.80	88	1.8	1.15	0.67	72	1.4
898	2.5	7.0	176	>10	0.5	3.8	168	5.6	0.75	3.25	160	4.6	0	1.5	122	2.8	0.25	0.9	96	1.5
1,027 [c]	2.75	6.9	104	>10	0.0	3.5	144	4.6	0.25	2.45	128	3.5	0.75	0.80	72	1.8	1.0	0.50	64	0.7
1,190	0.8	6.0	144	>10	0.0	3.5	168	4.5	0.0	2.4	168	3.6	1.0	0.5	96	1.5	1.25	0.25	80	0.5
1,546	1.75	7.0	168	>10	0.0	3.5	168	4.6	0.0	2.7	168	3.5	0.5	0.75	96	1.6	0.25	0.25	88	0.7
1,732	2.0	7.0	152	>10	0.0	3.0	152	5.8	0.5	2.5	168	3.6	1.0	0.80	96	1.2	1.5	0.45	96	0.8
1,888	2.5	7.0	152	>10	0.25	3.5	152	5.8	0.5	2.5	120	3.6	1.20	1.0	96	1.3	6.5	0.5	64	0.6
2,237	2.4	7.5	176	>10	0.0	4.0	176	6.5	0.5	3.5	125	4.5	1.0	3.75	112	1.9	0.5	0.75	112	1.3
2,312 [d]	2.0	4.0	144	>10	0.75	3.15	136	4.6	1.5	0.85	114	2.0	2.5	0.5	72	1.0	1.5	0.35	49	0.7
2,409	2.25	4.5	144	>10	0.5	3.2	136	4.5	1.0	1.0	96	2.0	2.5	0.6	72	1.0	1.0	0.3	49	0.6
2,473	2.5	4.3	144	>10	0.5	3.1	104	4.2	1.0	2.0	96	2.1	2.5	0.5	72	1.0	1.0	0.2	42	0.5
2,806	4.5	4.0	128	>10	2.0	1.5	120	3.5	1.75	0.5	80	1.1	3.0	0.25	48	0.0	4.0	0.0	40	0.0
2,899	4.0	4.6	128	>10	2.0	1.2	120	3.5	1.0	0.25	80	0.1	3.0	0.0	48	0.0	3.5	0.0	40	0.0
2,972	2.7	4.5	144	>10	1.6	0.8	130	1.7	1.8	0.2	104	0.1	2.3	0.1	72	0.0	1.6	0.0	64	0.0
3,104	5.2	2.6	88	>10	4.0	2.5	88	8.0	3.7	1.0	80	2.2	4.2	0.25	56	0.4	5.0	0.2	56	0.0
3,684	4.5	4.1	192	>10	2.0	0.9	90	2.2	2.5	0.4	64	0.8	0.4	0.0	48	0.4	0.3	0.0	48	0.0

[a] After one shut down, and adjustments.
[b] After warming up.
[c] Started up after shut down for oil change.
[d] Started up again: 2–3 minutes warm up time.

On other engines in poor condition with emission of higher concentrations of combustibles, the supply of supplementary air can be increased substantially. Since this will result in higher outputs of heat, the supply of cooling air to the external heat-exchangers can also be increased.

A portion of the heat generated in the catalytic units is dissipated by radiation to the faces of the afterburner casing which are at right angles to the passageways of the unit, while other amounts are lost by convection to the gases. For an engine in good condition, for example, a new engine, the emission of combustibles in the exhaust is sufficiently low that a simplified afterburner in which radiative cooling of the catalyst-impregnated unit is employed is sufficient to provide effective minimization of air pollution.

A particular advantage of the relationship of the surfaces of the catalytic units and the walls of the heat exchangers (including baffle plates 35) is that the catalytic surfaces are not at any point totally radiatively shaded from the heat exchangers by other parts of the catalytic units or by any part of the device itself. Moreover, radiation within the passageways materially assists in bringing about substantially uniform temperatures throughout the catalyst block.

Referring to FIGURE 5, there is shown an afterburner unit suitable for use with engines in good operating condition, in which a body **51** is provided with an inlet pipe **52** connected to a plenum chamber **54** formed in part by the top portion of the shell **51** and an extension connecting the body of the afterburner with the inlet. Outlet pipe **56** (here shown without a cover at the end of the pipe opposite to the end at which the stream of exhaust gases passes from the outlet, in order to show the entrance to the plenum chamber more clearly), is connected with plenum chamber **57** which is formed in part by the bottom portion of the shell **51** and the extension thereof connecting the body of the afterburner to the outlet pipe. Suspended within the body of the afterburner by brackets **58** at the four edges thereof is a ceramic catalyst unit **60** consisting of alternating flat and corrugated thin sheets of ceramic material which are cemented together at the crest of the corrugations by a ceramic cement. The corrugations and flat sheets form relatively long narrow passages. The surfaces of this block, which include the interior of the numerous passageways extending therethrough, is coated with a catalyst of the type described hereinabove. The catalyst block extends from side wall to side wall and from back to front of the shell **51**. The space between the portion of the heat-exchanger which is exposed to the inlet gases and the top of the shell of the afterburning unit **62** constitutes the inlet plenum **54** and the space between the exit face of the heat exchanger unit **60** and the bottom **63** of shell **51** constitutes the exit plenum **57** for the afterburning unit. Attached to the top **62** of the shell **51** as by welding or riveting are a plurality of heat-exchanger fins **64**, while attached to the bottom **63** of the shell **51** are a plurality of similar fins **65**. Fins **64** and **65** serve as heat exchange means between the afterburner shell and the atmosphere. The inner surfaces of the top **62** and bottom **63** of the shell **51** receive heat by radiation from the surfaces of the catalytic block **60**. It will be apparent that heat radiated from the interior of the passageways of the heat-exchanger unit **60** along lines of sight will impinge upon the bottom and top surfaces **63** and **62** respectively and will be lost by convection from fins **64** and **65** to the surrounding air. The operation of the device is similar to that of the operation of the combined muffler and catalytic afterburner of FIGURE 1, except that it has slightly less muffling effect and it may be necessary to provide an auxiliary muffler if the passageways in the catalytic block **60** are of relatively larger size compared to their length than preferred.

The unit shown in FIGURE 5 provides only one pass and employs radiative cooling of the catalyst unit, without the addition of internally finned heat-exchangers used in the afterburners described above. No flow of air is necessary other than that provided by movement of the car or by the fan if the unit is mounted near the engine block. Such a simplified unit is naturally less expensive to install and requires a minimum of accessories since a small supply of supplementary air can be provided ahead of the unit by a blower or a Venturi arrangement in the exhaust line.

A device of the type illustrated in FIG. 5, containing a platinum catalyst supported on a ceramic honeycomb of the size of one of the units of the type shown in FIG. 1, is employed with a six-cylinder automobile engine of the type described hereinabove. A sufficient amount (3 to 5 standard cubic feet per minute) of secondary air is introduced into the exhaust manifold varying with operating conditions between idling and cruise. A very satisfactory reduction in hydrocarbon and carbon monoxide content is achieved. The internal temperature of the catalyst does not rise above about 1300° F.

Another very useful embodiment of the invention is produced by employing an annular catalyst support rather than a block shaped support as shown in the embodiments of FIGURES 1 and 5 hereof. In this case, corrugated sheets are prepared as set forth hereinabove, and these are stamped out in the form of rings, the central opening being approximately equal in diameter to the width of the remaining portion of the ring. Suitable dimensions are a ring of about 6" diameter with a central opening of 2" diameter. A number of such sheets are stacked on one another and cemented together to form a cylinder, without flat sheets between them, with the corrugations in adjacent sheets running at an angle to the corrugations in the next sheet. Alternate sheets may have the corrugations running parallel to each other, although this is not necessary. A cylindrical stack of such sheets containing from 20 to 30 sheets, cemented together with a ceramic cement, and fired, constitutes a convenient unit for incorporation into a combined muffler and afterburner. Such units are used with a shell of generally cylindrical configuration, with appropriate baffles so that the exhaust gases flow through the central openings of the first unit, to the periphery of that unit, into the annular plenum formed by the space between the interior of the shell and the exterior of the catalyst support. From this space the flow of the gases is directed inwardly through the next unit and into the central cavity of that unit, thus causing a reversal of the direction of gas flow from that in the first unit. The exhaust gases flow into the central cavity of the third unit, through this unit outwardly to the periphery thereof, etc. The central cavities of the catalyst support units thus form inlet and outlet plenums for the gases in the central portion of the catalytic afterburner. In this way a change in the direction of flow is effected exactly as if the units were blocks mounted in a shell of the type described in FIGURES 1 and 2. Cooling means are provided on the external surface of the cylindrical shell and may consist of fin type radiators welded or bolted to the shell in the usual manner. It will be apparent that owing to the straight parallel nature of the corrugations in the individual sheets of the cylindrical units, radiative cooling is possible because the interior surfaces of the catalyst support are not shielded from the interior surface of the cylindrical shell. Thus, radiative heat from the catalyst support will impinge directly on the shell surface, which is the wall of the heat-exchanger, and thus will be carried away to the atmosphere.

Supplementary air for this unit can be supplied in the exhaust stream or at intermediate points in the afterburner itself, as described hereinabove with respect to the other embodiments specifically noted.

What is claimed is:

1. As an article of manufacture, a combined muffler and catalytic afterburner for an internal combustion engine, comprising, in combination, a body shell having an exhaust gas inlet adapted to receive exhaust gases from an internal combustion engine, a plurality of catalyst chambers defined by septa within said body shell having inlet and exit plenums connected for sequential flow of exhaust gases therethrough, the first said chamber being connected to said exhaust gas inlet, an equal plurality of ceramic catalyst supports provided with a multiplicity of parallel gas passageways and having oxidizing catalyst on their surfaces, said ceramic catalyst supports being disposed respectively within and substantially filling said catalyst chambers, and an outlet adapted to discharge exhaust gases into the atmosphere from said body shell connected with the exit plenum of the last catalyst chamber in sequence; the said catalyst chambers, catalyst supports and inlet and exit plenums being disposed so as to require change in direction of the flow of exhaust gases in each successive catalyst chamber; the exit plenum from each catalyst chamber except the last being continuous with the inlet plenum for the next catalyst chamber in sequence and being cooled by means coextensive with its external wall.

2. As an article of manufacture, a combined muffler and catalytic afterburner for an internal combustion engine, comprising, in combination a body shell and connected in sequence for the passage of gases therethrough, an exhaust gas inlet adapted to receive exhaust gases from an internal combustion engine, a first catalyst chamber having an inlet plenum connected to said inlet and containing a ceramic catalyst support in said chamber having a multiplicity of parallel ordered passageways disposed so as to require change in direction of the flow of exhaust gases from said inlet plenum and having an oxidizing catalyst on the surfaces thereof; an exit plenum from the said first catalyst chamber which is connected with the inlet plenum of an intermediate catalyst chamber, both of said plenums being cooled by means coextensive with an external wall of said plenums; a ceramic catalyst support in said intermediate catalyst chamber having a plurality of parallel ordered passageways disposed so as to require change in direction of the flow of exhaust gases from said plenums and having an oxidizing catalyst on the surfaces thereof; an exit plenum from the said intermediate catalyst chamber which is connected with the inlet plenum of a further catalyst chamber, both

of said plenums being cooled by means coextensive with an external wall of said plenums; a ceramic catalyst support in said further catalyst chamber having a plurality of parallel ordered passageways disposed so as to require change in direction of the flow of exhaust gases from said plenum and having an oxidizing catalyst on the surfaces thereof; and an exit plenum from the last catalyst chamber adapted to discharge the said exhaust gases into the atmosphere.

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