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Ferri

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[45] **June 17, 1975**

[54] **APPARATUS FOR REDUCING FORMATION OF OXIDES OF NITROGEN IN COMBUSTION PROCESSES**

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[22] Filed: **Nov. 22, 1972**

[21] Appl. No.: **308,721**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 72,985, Sept. 17, 1970, abandoned.

[52] **U.S. Cl.** **431/351**; 60/39.65; 60/DIG. 11

[51] **Int. Cl.** **F23d 13/00**; F23d 21/00

[58] **Field of Search** 431/2, 10, 11, 351, 352; 60/39.71, 261, 39.65

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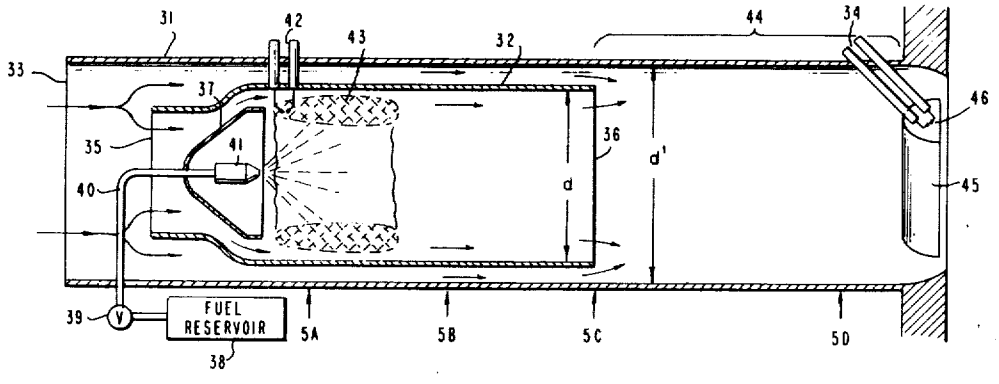
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Primary Examiner—Charles J. Myhre
Assistant Examiner—William C. Anderson

[57] **ABSTRACT**

Apparatuses and processes for reducing the formation of nitrogen oxides during combustion of fuel and air are disclosed. Fuel is completely vaporized and physically combined with air to provide a substantially uniform mixture on a molecular scale. This mixture will have an equivalence ratio of less than unity and will burn through formation of a thermal diffusion flame at temperatures below those encountered with stoichiometric combustion.

10 Claims, 14 Drawing Figures



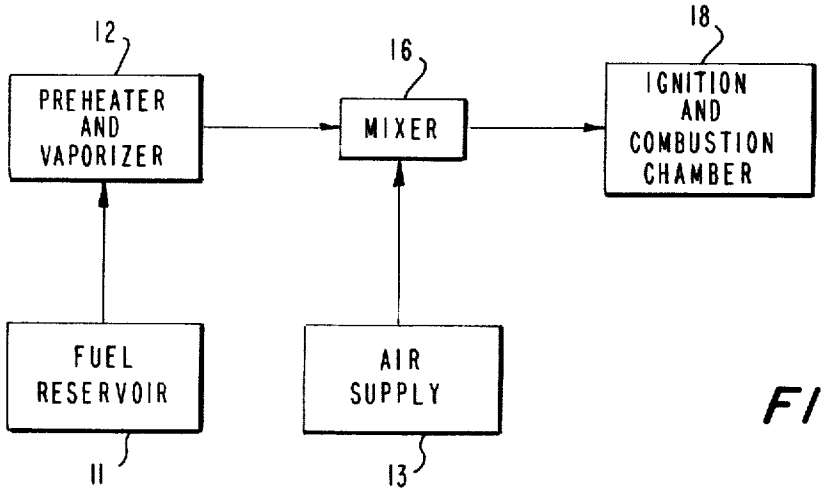

12
PREHEATER AND VAPORIZER
16
MIXER
18
IGNITION AND COMBUSTION CHAMBER
FUEL RESERVOIR
11
AIR SUPPLY
13

FIG. 1

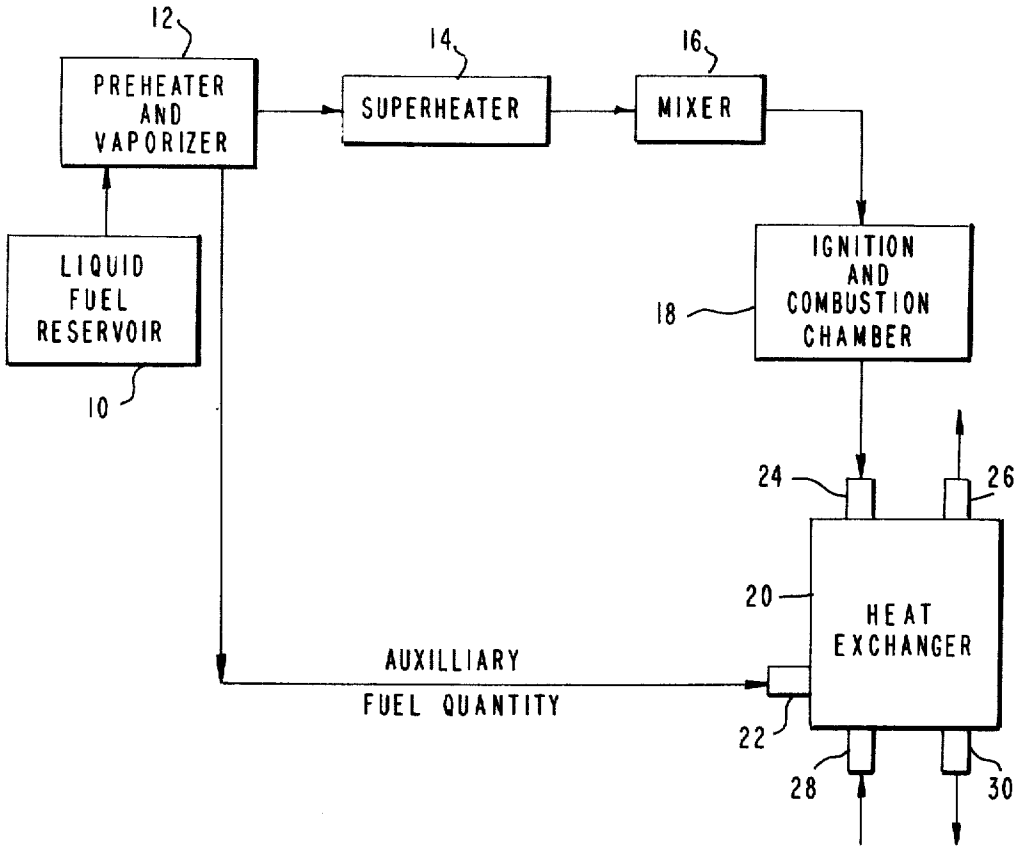

12
PREHEATER AND VAPORIZER
14
SUPERHEATER
16
MIXER
LIQUID FUEL RESERVOIR
10
IGNITION AND COMBUSTION CHAMBER
18
24
26
20
HEAT EXCHANGER
AUXILLIARY FUEL QUANTITY
22
28
30

FIG. 2

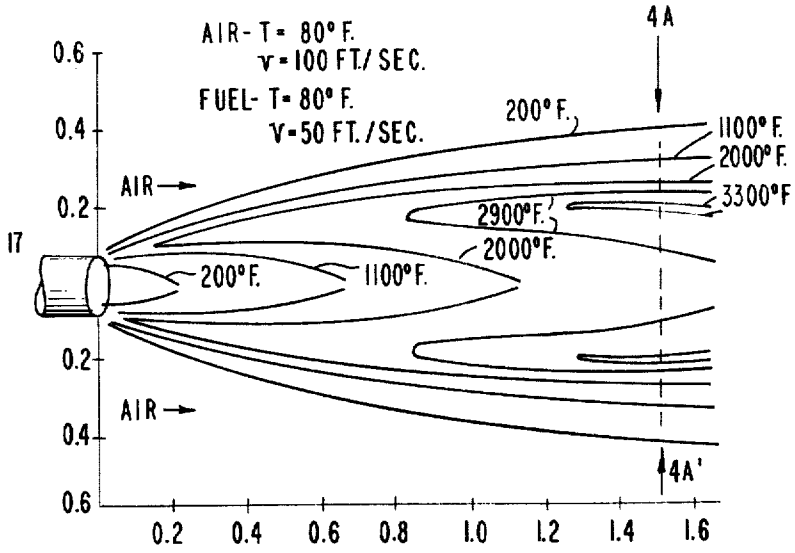


FIG. 3A

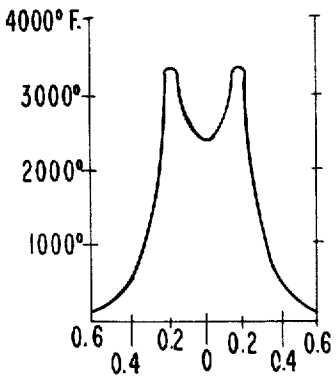


FIG. 4A

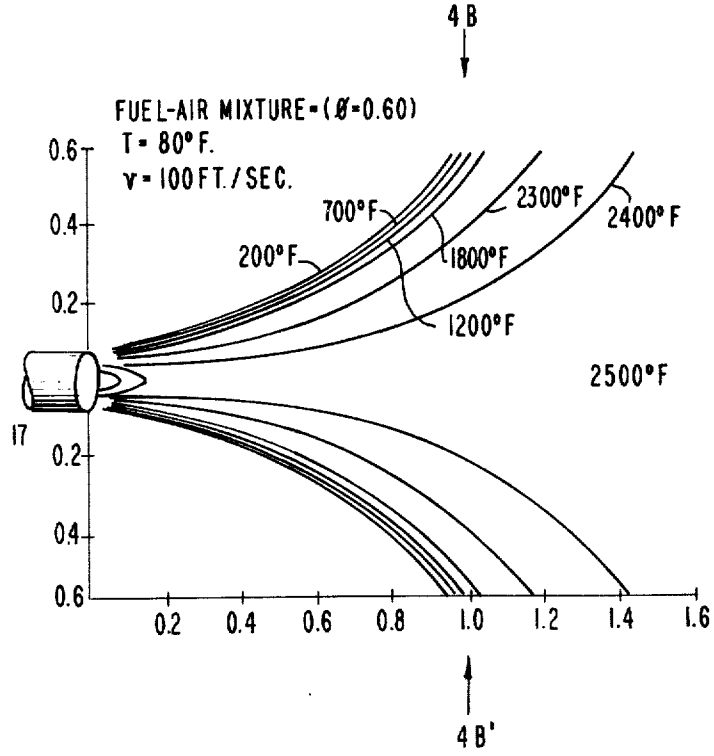


FIG. 3B

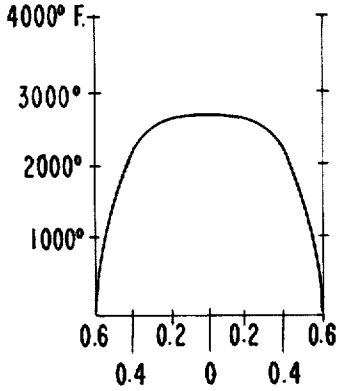
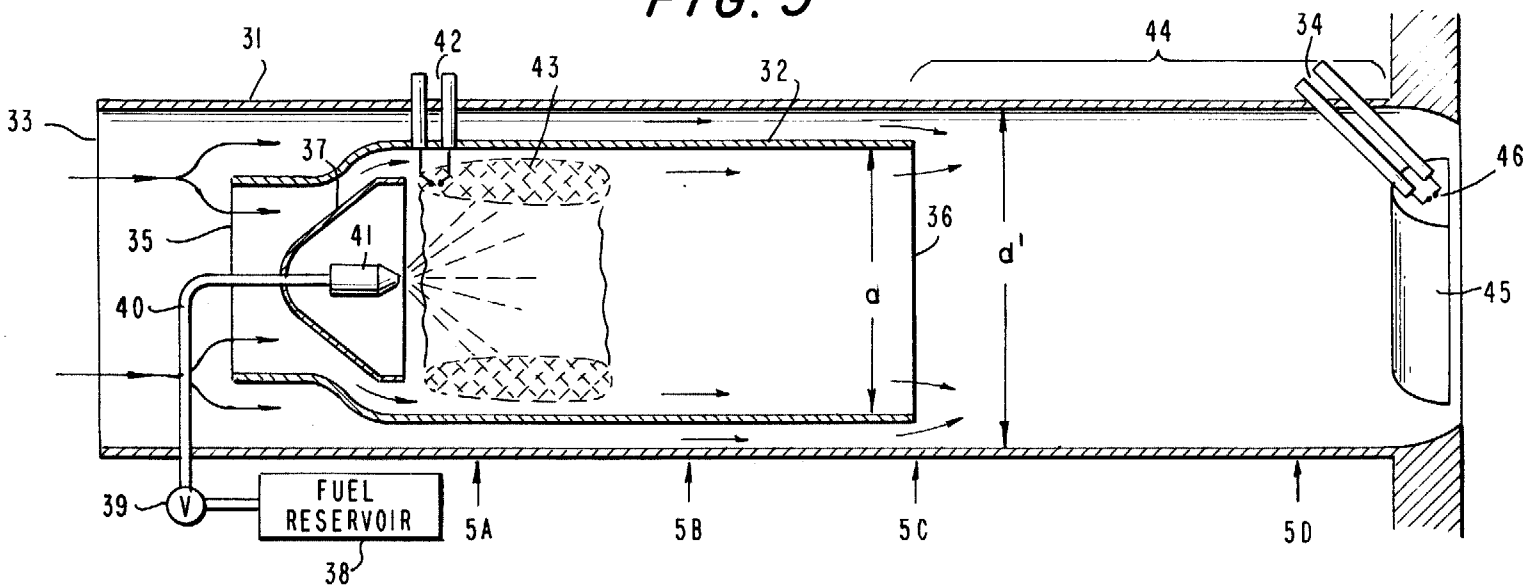


FIG. 4B

FIG. 5



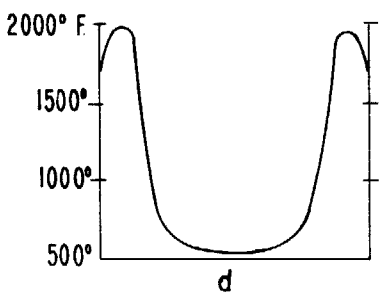


FIG. 5A

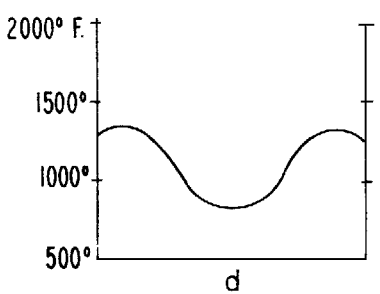


FIG. 5B

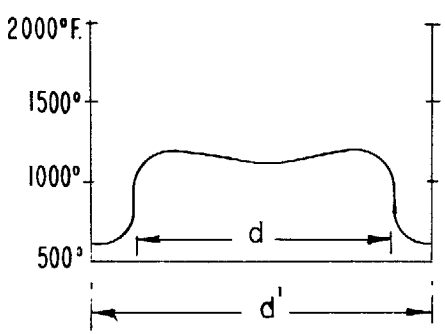


FIG. 5C

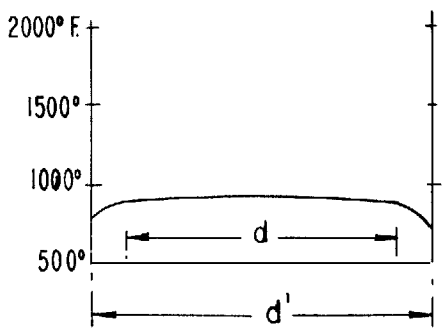


FIG. 5D

FIG. 6

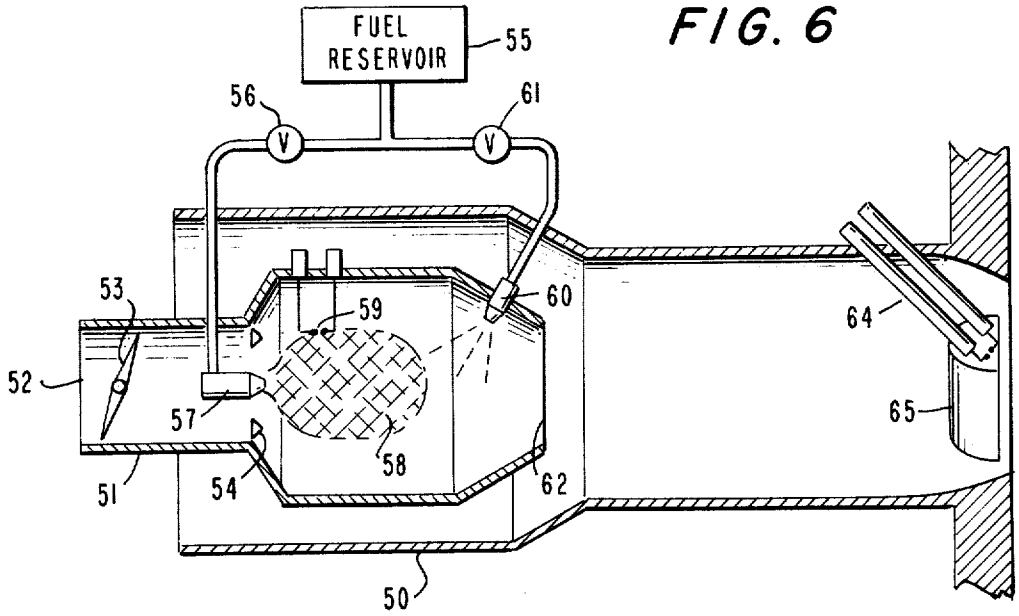
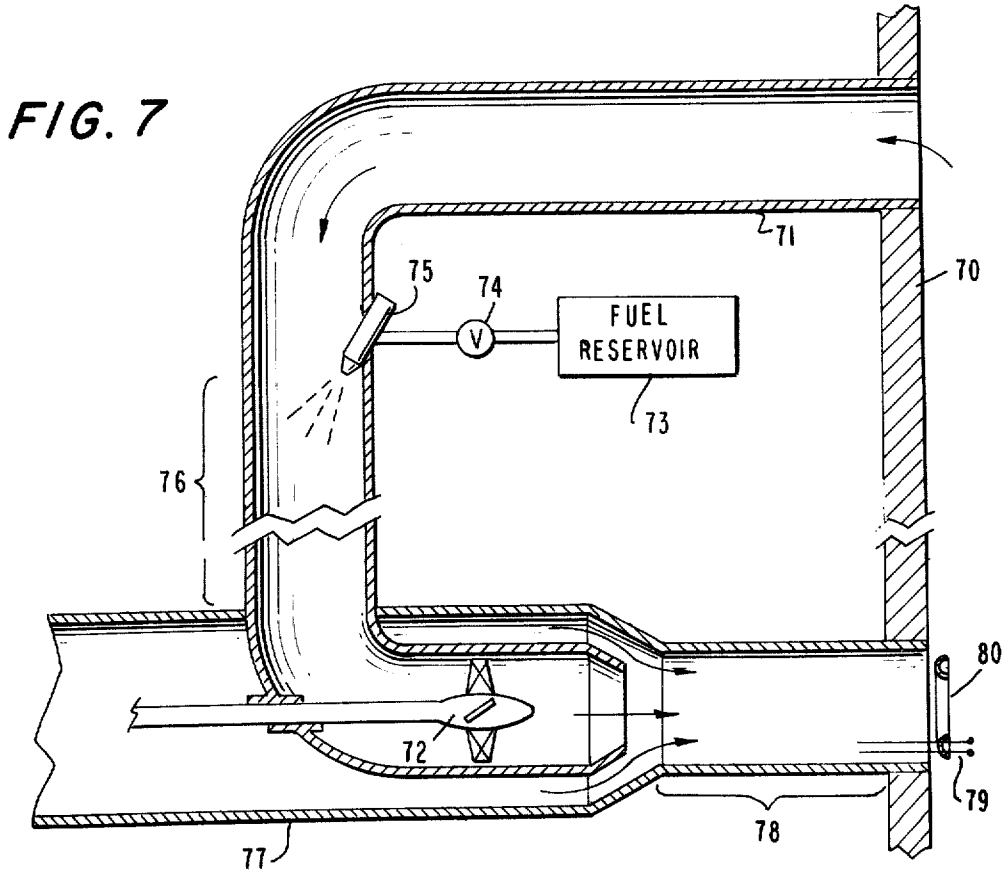

FUEL RESERVOIR
55
56
61
V
V
53
59
60
64
52
57
58
65
51
54
62
50

FIG. 7


71
70
75
74
V
FUEL RESERVOIR
73
76
80
72
79
78
77

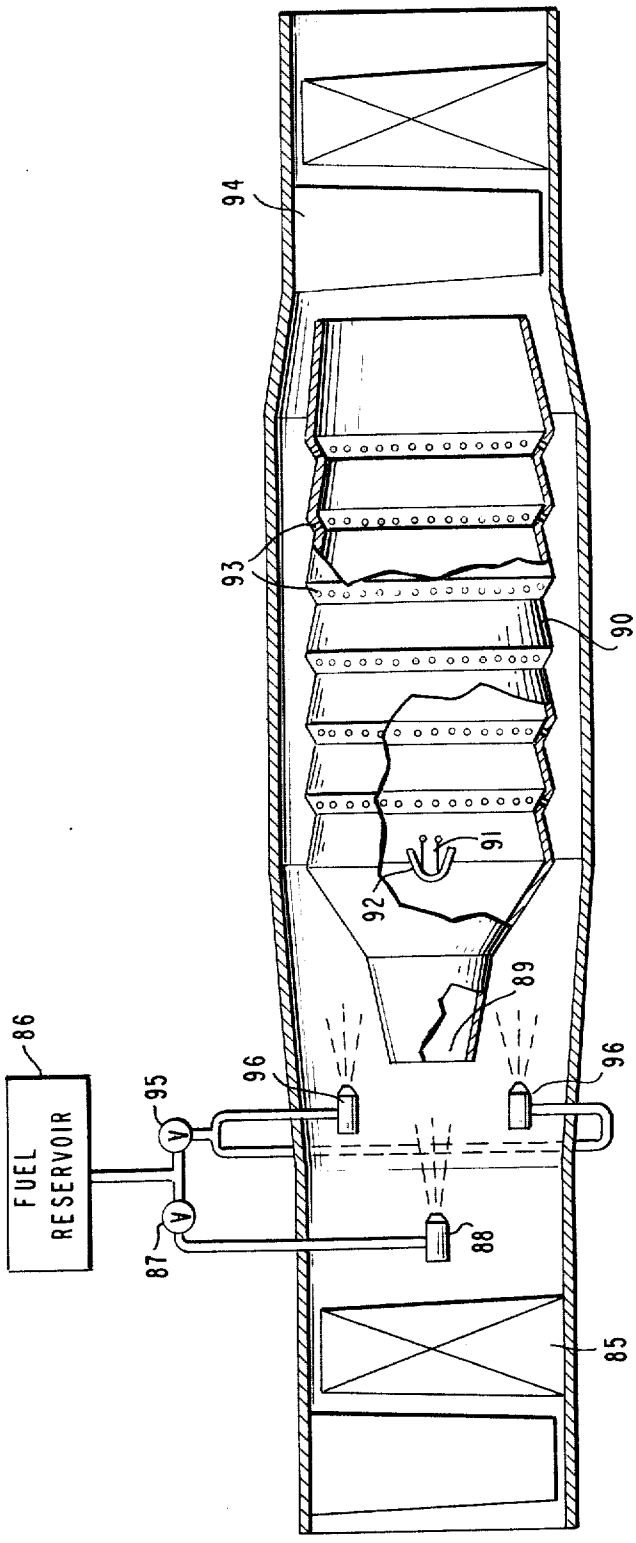


FIG. 8

APPARATUS FOR REDUCING FORMATION OF OXIDES OF NITROGEN IN COMBUSTION PROCESSES

CROSS-REFERENCE

This is a continuation-in-part of Ser. No. 72,985 filed Sept. 17, 1970, now abandoned. Applicant hereby incorporates by reference into this application the entire contents of his prior application Ser. No. 72,985.

DETAILED DESCRIPTION

In nearly all combustion processes in which fuel is burned in the presence of air, the resultant products include oxides of nitrogen such as nitrous oxide. Nitrous oxide, in particular, is a serious pollutant which can produce an irritant effect upon humans and is a major factor in the formation of such environmental problems as smog.

It is an object of the present invention to provide an improvement in the combustion of fuels which improvement reduces substantial formation of nitrogen oxides in known combustion processes.

It is a further object of the invention to provide apparatuses for combustion of such fuels, which apparatuses result in a reduction and minimization of oxides of nitrogen formation.

Other objects of the present invention will be apparent from the following description and accompanying drawings in which:

FIG. 1 is a functional schematic diagram of the fundamental arrangement used to prevent substantial formation of oxides of nitrogen in combustion processes, in accordance with the present invention;

FIG. 2 is a functional schematic diagram of a more complex arrangement used to prevent substantial formation of oxides of nitrogen in combustion processes, in accordance with the present invention;

FIG. 3A is a diagram of a typical isothermic development of a mass diffusion flame;

FIG. 3B is a diagram of a typical isothermic development of a thermal diffusion flame;

FIG. 4A is a plotting of temperatures generated in a typical mass diffusion flame through transverse section of lines 4A–4A′ of FIG. 3A;

FIG. 4B is a plotting of temperatures generated in a typical thermal diffusion flame, through transverse section of lines 4B–4B′ of FIG. 3B;

FIG. 5 is a schematic elevation in cross section of a typical apparatus according to the present invention;

FIGS. 5A, 5B, 5C and 5D are plottings of typical temperatures generated transversely across the interior of the embodiment shown in FIG. 5 at points 5A, 5B, 5C and 5D, respectively;

FIG. 6 is a schematic elevation in cross section of an alternative embodiment of the apparatus according to the present invention;

FIG. 7 is a schematic elevation in cross section of a third embodiment of the apparatus according to the present invention; and

FIG. 8 is a schematic elevation in partial cross section of a fourth embodiment of the apparatus according to the present invention.

It has been recognized that the formation of various undesirable oxides in combustion processes can be traced to the occurrence of extremely high temperatures during the combustion of fuel. Thus in U.S. Pat. No. 3,228,451, a method of burning fuel is described

in which the formation of sulfur trioxide (produced by the oxidation of sulfur dioxide) can be reduced or eliminated by first burning the fuel in a fuel-rich environment, cooling the products of the combustion and mixing the cooled gas with additional air, the additional air being added being such that the ratio of total air to total fuel is no greater than about 5% in excess of the stoichiometric ratio. As a result of this two-step combustion, the overall air:fuel ratio does not reach the critical value of about 14:1, this ratio resulting in the high temperatures at which sulfur trioxide is formed.

Similarly, in U.S. Pat. No. 3,048,131 a two stage combustion of fuel is described which reduces the formation of nitrogen oxides. In this method, the initial combustion is again one of fuel-rich mixture with the remaining air being added thereafter so that complete combustion of the fuel is retarded and the maximum temperature of the flame reduced, the absence of sufficient oxygen in the hottest part of the flame apparently causing the available oxygen to combine with carbon rather than with nitrogen.

In both of the above typical processes, and in most combustion processes, the actual combustion involves the generation of a mass diffusion flame, combustion occurring as the air and fuel come in contact with one another. This is true even in those cases in which the fuel is atomized since combustion can be observed to take place in a laminar diffusion flame in a penumbra about the individual fuel droplets. Thus the concentration of the vaporized fuel near the surface of the droplet is 100% with the equivalence ratio (ϕ) [fuel:air/(fuel:air) stoichiometric] being infinity. At the interface of surrounding air and the fuel droplet, the equivalence ratio approaches unity and below unity in the flame surrounding the droplet. Consequently in any such process, regardless of the equivalence ratio for the overall system, whether it be fuel-rich or fuel-lean, there will be areas within the mass diffusion flame in which the equivalence ratio is approximately one. The high temperatures generated when the stoichiometric amounts of fuel and air burn will be present and will result in formation of nitrogen oxides which are thus present in the exhaust.

As can be seen from FIGS. 3A and 4A, when fuel is emitted from an outlet 15, combustion occurs as the fuel and air mix and ignite. Again the equivalence ratios vary from infinity at the point at which fuel exits from the outlet to zero where air enters the combustion chamber. Various intermediate values will of course exist, including the stoichiometric ratio ($\phi = 1$). Consequently, not only are the temperatures not uniform across the flame, high temperatures are generated where the equivalence ratio is one. Hence as shown on FIG. 4A, which corresponds to the temperature cross section at 1.0 foot from the flame origin, peaks as high as 3,300°F occur. Depending upon the fuel and conditions of combustion, even higher temperatures can occur.

The present process utilizes a combustion technique the mechanism of which is totally distinct. In particular, the present process provides for the combination of the fuel and air in such a fashion that eventual combustion takes place through a thermal diffusion flame rather than a mass diffusion flame. As a result, it is possible through the utilization of a predetermined amount of air and fuel to operate at equivalence ratios below one. Such combustion occurs according to the present in-

vention uniformly at the temperature for the given equivalence ratio without any localized stoichiometric combustion. At such ratios, and because of the formation of a thermal diffusion flame rather than a mass diffusion flame, the temperatures associated with stoichiometric combustion are completely avoided, even on a local basis, and the actual temperatures at which the given mixture will burn can thus be controlled so that the formation of nitrogen oxide is prevented.

As can be seen from FIGS. **3B** and **4B**, when a mixture of air and fuel which is uniform on a molecular level is ignited by passage past a pilot ignitor **17**, the combusion isotherms are uniform. For the particular mixture shown in FIG. **3B** ($\phi = 0.60$), the maximum temperature reached is 2,500°F. The increase in temperature from the entrance temperature of 80°F to this maximum is regular and corresponds to uniform combustion as observed travelling through the combustion chamber

The operation of the present process can be seen from FIGS. **1** and **2**. The process utilizes any liquid or solid fuel stored in fuel reservoir **11**. This fuel is first heated and vaporized, through various techniques which are described in more detail hereafter in preheater and vaporizer **12**. It is important to note that this vaporization must be complete and that simple atomization which has been widely practiced heretofore in combustion processes will not suffice since simple atomization will not generate the requisite thermal diffusion flame.

The vaporized fuel is next combined in mixer **16** with air from air supply **13**. The amount of air added to the fuel does not matter, provided it is at least equal to the stoichiometric amount. In sharp contrast to the prior art for example, it is permissible, and often desirable, to add a large excess of air. Thus an excess of air over the stoichiometric amount can be utilized without concern that this excess will result in formation of oxides. This aspect of the invention is particularly advantageous in such applications as turbines since it is possible to work at the low equivalence ratios required for turbine operation; e.g., equivalence ratio 0.2.

The air and vaporized fuel are combined at a first station upon entering mixer **16** and then transferred to a second station, the ignition and combustion chamber **18**, where combustion will occur. It is critical to the present invention that the passage from the first station to the second station results upon arrival at the second station in a substantially uniform mixture of the air and fuel on a molecular scale. Moreover, it is necessary that this passage takes place without combustion of the two components. Thus, the passage must be conducted at a speed greater than the flame propagation speed of the particular mixture. It is possible, for example, that the vaporized fuel will be at a temperature which would permit immediate combustion with the air upon contact of the two but pursuant to the present process, the mixture is transported to the second station with sufficient speed that flame propagation cannot take place. Moreover, ignition of the mixture occurs subsequent to the arrival of the mixture at the second station. Since this combustion is accompanied by formation of the thermal diffusion flame, it is important that the vaporized fuel and air are transported to the second station at a speed in excess of the flame propagation speed, thereby preventing combustion of the mixture prior to arrival at the second station.

Finally, it is critical to the invention that the vaporized fuel and the air are thoroughly mixed so as to form a uniform mixture on a molecular level. It is readily apparent that if the fuel is not completely vaporized, such a uniform mixture of molecules will not be achieved. Moreover, even if the fuel is completely vaporized but is not thoroughly mixed with the air when the two components are ignited, ignition will occur through formation of a mass diffusion flame, thereby defeating the basic objective of the present invention.

Referring to FIG. **2**, liquid fuel from a reservoir or tank **10** is passed or transferred to heating apparatus **12**. The apparatus **12** serves to preheat the fuel from the tank or reservoir **10**, and to raise the temperature of the fuel until it becomes fully vaporized. The function of the preheater and vaporizer **12** is such that the temperature of the liquid fuel introduced therein is raised to the level so that the entire fuel within the preheater becomes gaseous. The heating of the fuel within the unit **12** can take place in the absence of air or may be accomplished by combustion of a fuel-rich mixture. The temperature at which the fuel transforms to the gaseous state varies with the specific fuel used and with the pressure level prevailing within the preheater unit **12**. Thus, if the pressure within the heating and vaporizing device **12** increases, the temperature at which the fuel transforms to the gaseous state will also increase. For the common grade fuel oils, the temperature at which the fuel becomes gaseous, is approximately 500°F. at atmospheric pressure.

The fuel is heated and transformed to the gaseous state to avoid the disadvantages resulting from mixing liquid droplets of the fuel with air, as it commonly prevails in the usual combustion devices, as discussed above.

It is of course not necessary that the fuel be maintained at the temperature of 500°F., for example, at which point common grade fuel oils are vaporized at atmospheric pressure. Definite advantages can be realized in some applications when the fuel is further heated, for example, to temperatures of the order of 1,000°F. At this higher level in temperature, the fuel will pyrolyze, and break down chemically to form a mixture of lower molecular weight species. Further heating of the vaporized fuel will not result in material reduction of nitrous oxide formation but significant improvements can be obtained from the viewpoint of combustion efficiency as for example in large power plants. For this reason, the vaporized fuel from the preheater and vaporizer may be introduced into a superheater **14** where it is heated to the advanced temperatures and allowed to break down chemically. As a result of the superheating of the gaseous fuel and resultant chemical break down of the fuel, less carbon and carbon monoxide remain and such components as methane, propane, and ethane, for example, are formed. With reduced carbon and carbon monoxide present in the exhaust gases, less of the available energy is discarded, and therefore the operating efficiency is increased.

After the fuel has been vaporized in the unit **12** and further heated within the unit **14**, the resultant gaseous fuel is passed to a mixer **16** in which the gaseous fuel is intermixed with the predetermined amount of air also passed into the unit **16**. The gaseous fuel and the air become thoroughly intermixed on a molecular level within the mixing unit **16**, so as to form a homogeneous

mixture of gases. The amount of air with which the gaseous fuel is intermixed determines the fuel/air equivalence ratio which is selected and controlled to assure that the temperature of the mixture upon ignition will not exceed, and generally be far below, the upper limit of approximately 2,500°F. Thus, the mixer **16** adjusts the amount of air intermixed with the gaseous fuel to result in the desired fuel/air ratio as, for example, 4 to 5% ($\phi = 0.6$ to 0.75). The particular equivalence ratio selected will of course depend upon the type, design and application of the mechanical installation involved in the actual combustion process.

After the gaseous fuel and air have been thoroughly intermixed so that a homogeneous gas mixture is delivered to the combustion chamber, the mixture of gases is ignited through conventional means, a sparkplug, glow plug, pilot flame or other suitable ignition device. The mixer and combustion chamber may be combined so that such ignition of the gases may take place, after mixing, within mixer **16** itself, or preferably the mixture of gases is first transferred or passed to an ignition and combustion chamber **18.** Accordingly, the ignition device in the form of a spark plug as used in automotive engines, for example, may be either located directly within the mixing chamber **16,** or within a separate mixing and combustion chamber **18.**

The ignition of the gaseous mixture of fuel and air takes place at substantially one point within the volume occupied by the mixture. The flame which results from the ignition process, propagates rapidly through the mixture by the process of turbulent heat conduction. In spreading through the mixture in this manner, the temperature of the mixture increases monotonically, from the initial gas temperature to the final temperature produced in response to the particular fuel/air equivalence ratio which is utilized. As already noted, the fuel/air ratio is selected on the basis that the final temperature achieved by the mixture during the monotonic temperature function, does not exceed, and is generally below, approximately 2,500°F., at which temperature level substantially no nitrous oxide is formed.

If the heat resulting from the combustion of the gaseous mixture were to be used in a power plant, for example, then the hot gases from the combustion chamber **18** may be passed or circulated through a heat exchanger **20.** The heat from the burned gases is transferred within the heat exchanger to a working fluid such as water, for example, which is circulated through a coil in the heat exchanger. Thus, the heat exchanger **20** is a conventional unit in which the working fluid is introduced through inlet **28,** circulated through a coil (not shown), which is in turn in thermal contact with the hot combustion gases being introduced through inlet **24.** After the working fluid has been adequately heated, it may be removed at outlet **30** and passed to a turbine, for example, to extract the useful energy contained within the working fluid. The spent combustion gases may be removed at outlet **26.**

In view of the fact that the fuel and air proportions are adjusted to an equivalence ratio of less than one in order to prevent the temperature of combustion from exceeding approximately 2,500°F., all of the oxygen available in the air is not consumed. This is a result of the lean mixture which can be advantageously used in the combustion process. When dealing with heat exchangers and boiler-type of applications, it is important that all of the available oxygen supplied through a given unit be utilized in order to achieve high process efficiency. For example, the apparatus in existing power plants is designed to supply, at capacity, a given volume of air. If, on the other hand, all of the available air (oxygen) is not utilized, the full capacity of the power plant is not being realized even though air is being supplied at full capacity. The process efficiency of the plant is thus reduced. To overcome this problem resulting from use of a lean mixture for combustion, additional fuel may be introduced into the heat exchanger **20.** This is done of course at a point where the gas temperature has dropped sufficiently so that additional combustion will not result in the temperatures exceeding 2,500°F. Accordingly, an auxiliary quantity of fuel from the preheater and vaporizer **12** may be injected into the heat exchanger **20** through the auxiliary inlet **22,** in order to produce the additional, auxiliary combustion whereby all of the available oxygen in the air is consumed. This auxiliary combustion is identical to the first, i.e., by thermal diffusion flame. The temperature function within the heat exchanger **20,** is thus a saw-tooth shape resulting from cooling of the combustion gases to a sufficient lower temperature with the addition of auxiliary fuel through the inlet **22** causing the temperature to rise again. As noted, the location in the heat exchanger **20** at which the inlet **22** is placed, is such that the final temperature of the burned mixture does not exceed the 2,500°F. limit.

Referring now to FIG. **5,** there is depicted a specific embodiment of a clean exhaust burner according to the present invention. This burner is suitable, for example, for the combustion of liquid fuel such as No. 2 or No. 4 fuel oil. Obviously minor mechanical and dimensional adjustments may be made for other fuels. The burner comprises two concentric ducts of any desired cross section, a blast tube **31** forming the outer section and a vaporizing tube **32** forming the inner section. Blast tube **31** terminates in an open end **33** through which air enters under the action of a fan, compressor or similar device (not shown). The other end of blast tube **32** terminates in the combustion chamber of which only a portion of the wall **34** is shown. Vaporizer tube **32** which is concentrically disposed within blast tube **31** terminates in an open end **35** through which air enters and, at the other extreme, a second open end **36** through which the vaporized fuel emerges. Disposed within vaporizer tube **32** is a deflector **37** whose axial position may be varied to control the amount of air entering the vaporizer. Fuel from fuel reservoir **38** is passed through appropriate valve means **39** to fuel injector **41** through appropriate conduiting **40.** A portion of the air entering open end **33** of the blast tube further passes through open end **35** of the vaporizer, around deflector **37** and mixes with the injected fuel, whereupon it is ignited by primary ignitor **42** with the resultant formation of a flame diagrammatically shown at **43.** The amount of fuel introduced by fuel injector **41** is adjusted so that the bulk averaged equivalence ratio within the vaporizer tube is considerably in excess of unity; i.e., a fuel-rich mixture with ϕ between 5 and 15. Since there is insufficient oxygen in the vaporizer tube to react with all the fuel, the excess is vaporized by the heat produced by the limited combustion. While this initial combustion takes place through a mass diffusion flame, as in the prior art, the generation of nitrogen oxides is limited due to the insufficient air in the vaporizer tube.

In addition to the air entering the open end **33** of the blast tube and then passing through the open end **35** of the vaporizer tube, additional air entering open end **33** of the blast tube passes about the outside perimeter of the vaporizer tube. This air passing between the inside wall of the blast tube and the outside wall of the vaporizer tube effects a heat exchange, cooling the wall of the vaporizer and becoming preheated itself in the process.

The vaporized fuel emerging from open end **36** of vaporizer **32** then comes in contact with the air which has been diverted to between the outside wall of vaporizer tube **32** and blast tube **31.** These two components are then thoroughly mixed by turbulence in section **44** of blast tube **31.** Thus section **44** is of sufficient length to ensure that the vaporized fuel and air constitute a uniform mixture on a molecular level by the time they emerge into the combustion chamber.

Upon entrance into the combustion chamber, the mixture of vaporized fuel and air encounter flame holder **45** which can be of any conventional shape and merely serves to provide a station of reduced velocity in order to permit the formation of flame. The mixture of vaporized fuel and air is thus ignited by a secondary ignitor **46.** As discussed above, this ignition will take place through formation of a thermal diffusion flame emanating from flame holder **45** upon passage of the mixture of vaporized fuel and air around flame holder **45.**

The length of the vaporizer tube **32** and blast tube **31** are matters of design preference. Vaporizer **32** should be of a length sufficient to permit the hot gases produced by the initial combustion to thoroughly diffuse into the unburned gases and fuel so as to convey the heat necessary for vaporization of the excess fuel with production of a gaseous mixture of thoroughly uniform temperature. Similarly, the length of mixing section **44** should be sufficient to permit a thorough mixture of vaporized fuel and air on a molecular level and a thoroughly uniform temperature. These considerations are depicted in FIGS. **5A, 5B, 5C** and **5D.** As will be seen in FIG. **5A,** the temperature gradient within vaporizer tube **32** at the point of ignition varies from a high approaching 2,000°F. to a low of about 500°F. By the time this mixture has passed approximately half-way through the vaporizer tube **32,** the temperature gradient ranges from about 1,000° to about 1,400°F., as shown in FIG. **5B.** As seen in FIG. **5C,** the base of which has been enlarged to include the air being introduced about the circumference, the temperature of the hot gases emerging from the vaporizer tube is fairly uniform, although the air emerging from the circumference about the blast tube **31** is considerably cooler. By the time this mixture reaches the entrance to the combustion chamber, the temperature and composition are fairly uniform, as shown in FIG. **5D.** It is this uniform mixture which is ignited in the combustion chamber. At this stage, the overall equivalence ratio is less than unity, as a result of the introduction of the by-passed air to the vaporized fuel.

The overall design of this apparatus is such that the velocity of air and fuel passing through it is greater than the flame propagation speed for the given mixture. As a result, the mixing which takes place within the tube will not be accompanied by combustion. In order to permit the initial combustion utilized in the vaporization of the fuel to occur locally in the area **43,** the vaporizer tube is designed to provide a limited reduction in overall velocity at the locality of the initial combustion. This may be performed, for example, through constriction of the inlet to the vaporizer tube and the introduction of baffles such as **37.**

FIG. **6** depicts an alternative design for a clean exhaust burner operating with fuel similar to those employed in the embodiment shown in FIG. **5.** Disposed within blast tube **50** is vaporizer **51.** The fraction of air entering the vaporizer tube **51** through its open end **52** is controlled by appropriate valve means such as butterfly **53.** Stabilization of the combustion in the first region is accomplished through a set of swirl vanes **54.** Fuel from fuel reservoir **55** is monitored by valve means **56** and injected into the vaporizer **51** through fuel atomizer **57.** The amount of fuel introduced is such as will provide a stoichiometric flame in the area **58,** having regard for the amount of air permitted to be introduced into the vaporizer by butterfly valve **53.** The ignition of the atomized fuel and air introduced into the atomizer is accomplished through ignitor **59.** Into the resultant stoichiometric flame is then injected additional fuel through fuel injector **60,** the amount of fuel being controlled by valve means **61.** The hot gases caused by combustion in the area of **58** thus vaporize the additional fuel introduced by fuel injector **60.**

The vaporized fuel and the combustion gases from the primary combustion in area **58** then emerge from the vaporizer at open end **62** and mix with air which has passed between the outside wall of vaporizer tube **51** and the inside wall of blast tube **50.** Complete mixing of the vaporized fuel and air then occurs in mixing section **63** of blast tube **50.** The uniform mixture of vaporized fuel and air are then passed into the combustion chamber and ignited by a secondary ignitor **64** with formation of a thermal diffusion flame at flame holder **65.**

Mixing section **63** is constructed in this embodiment of a reduced cross sectional area so that the gas velocity in this section is higher than the flame propagation speed of the particular mixture. By reducing the cross section of the blast tube in the mixing section, vis-a-vis the inlet area of the blast tube, and expanding the cross section of the vaporizer tube in the area of combustion, vis-a-vis the inlet section of the vaporizer tube, it is possible to isolate the primary combustion to area **58,** pass the vaporized fuel and mixed air through the mixing section without combustion, and permit complete combustion by thermal diffusion flame upon entrance of this mixture into the combustion chamber.

It can thus be seen that the two designs depicted in FIGS. **5** and **6,** while differing in mechanical detail, are functionally identical. It is thus possible to alter mechanical features, such as the type and location of the fuel injectors, ignitors and flame holders so long as fuel is completely vaporized in a fuel-rich environment and thereafter thoroughly premixed with sufficient air to provide an equivalence ratio less than one and passage of this mixture with complete blending to a combustion station at a speed faster than the flame propagation speed of the given mixture.

It is of course possible to utilize means of vaporization other than actual ignition of the fuel in a primary combustion. Thus FIG. **7** depicts a third embodiment of the invention suitable for example with use of utility grade fuels such as No. 6 oil. Such fuels are highly viscous and contain a sizeable fraction of chemically bound nitrogen. With such fuels, it is desirable to effect

vaporization in the absence of a flame and to permit the release of the chemically bound nitrogen with recombination of the released atomic nitrogen at sufficiently low temperatures that nitrogen oxide is not generated.

In the embodiment of FIG. 7, flue gases are removed from furnace 70 through conduit 71 by the action of fan 72. Fuel from fuel reservoir 73 is channeled through valve 74 to heavy oil atomizer 75 where it is sprayed into the hot fuel flue gases. Depending upon the nature of the specific fuel, it may be advantageous to preheat it prior to atomization. The atomized fuel vaporizes in the hot flue gases being carried towards fan 72. Although vaporizer section 76 is telescoped in FIG. 7, its length should be sufficient not only to effect complete vaporization, but also pyrolysis of the vaporized fuel and recombination of the released atomic nitrogen produced by this pyrolysis. Moreover, it is desirable that fan 72 be placed sufficiently downstream from atomizer 75 so that it can operate in an environment of considerably reduced temperature. Air enters blast tube 77 under the action of a fan or compressor (not shown) in sufficient quantity to provide an overall lean mixture with the vaporized fuel upon entrance into mixing section 78. Again, as in the above embodiments, the length of mixing section 78 should be sufficient to ensure a homogeneous mixture, on a molecular level, of the vaporized fuel and air. This homogeneous mixture is ignited by ignitor 79 on flame holder 80. Again the velocity of the components through mixing section 78 should be sufficient to preclude propagation of a flame prior to arrival at flame holder 80 and ignitor 79.

It is significant to note that appreciable oxides of nitrogen will not be formed in the vaporizer section because of the locally fuel-rich environment. When the mixture becomes fuel-lean, namely in the vaporizer section and combustion chamber, the temperature limitations similarly prevent formation of oxides of nitrogen.

FIG. 8 depicts a further embodiment of the present invention in which the clean exhaust systen is incorporated in a gas turbine combustor suitable for stationary use in the generation of power or in automotive, aircraft or marine propulsion. In this embodiment, air enters the combustor and is compressed and heated by compressor 85. Although the compressor is schematically depicted as an axial flow compressor, other conventional compressors, such as a centrifugal compressor, can be employed. During low power operation such as engine idle, fuel from fuel reservoir 86 is monitored through valve 87, optionally with preheating (not shown), to fuel injector 88. The atomized fuel is vaporized upon contact with the hot compressed air exiting from compressor 85 and flows downstream to mouth 89 of combustion can 90. The relative spacing of mouth 89 of combustion can 90 and fuel injector 88 is such that all of the fuel is substantially completly captured by mouth 89. Disposed within combustion can 90 is ignitor 91 and flame holder 92. These components are located sufficiently downstream from injector 88 to ensure that the fuel is completely vaporized and thoroughly mixed with the air when ignition occurs. The amount of fuel introduced through fuel injector 88 is such that the equivalence ratio of the mixture of air and vaporized fuel arriving at ignitor 91 is less than unity; e.g., approximately 0.7. The uniform mixture of vaporized fuel and air is thus ignited and burns without producing appreciable amounts of oxides of nitrogen. In this low power operation, additional air flows over the outside surface of combustion can 90 and enters the interior of the combustion can through a plurality of orifices 93 disposed on the outside surface of the can. This additional air mixes with the products of combustion, reducing the local equivalence ratios and the temperature of the combustion products to that required for low power operation upon entrance of the gases to turbine entrance station 94.

To convert to high power operation, additional fuel from fuel reservoir 86 is monitored through valve 95 to auxiliary fuel injectors 96. Fuel injectors 96 are designed so that their fuel spray does not impinge upon the walls of the combustor. Rather the atomized fuel is vaporized by the hot compressed air and the vaporized fuel and air are then thoroughly mixed in their passage downstream. This additional vaporized fuel and air is carried over the outside surface of combustion can 90 and introduced there through orifices 93. Since this additional fuel enters downstream from ignitor 91, further combustion occurs upon entrance of the vaporized fuel and air into combustion can 90. While the fuel mixture originating from injector 88 is lean (an equivalence ratio of 0.7), the mixture originating from fuel injectors 96 is still leaner and thus the equivalence ratio at the point of exit from the combustion can 90 at turbine entrance station 94 is below this value; e.g., equivalence ratio of 0.2. Because the present process permits combustion at such low equivalence ratios, one achieves not only a reduction in oxide formation but also a reduction in operating temperature. Consequently, the components of the turbine are not subjected to excessive heat.

It is to be understood that the foregoing embodiments are presented largely schematically and solely for the purpose of exemplification. Thus for example the type of compressor, the nature of the turbine, the structure of the flame holder and ignitor, the presence of swirl vanes, the mixing mechanism and the number or type of fuel injectors do not bear on the basic nature of the present invention. Hence the foregoing description and drawings represent typical embodiments of the present invention but are not intended as limitations on the scope thereof, it being apparent that the invention can be practiced through obvious modifications and rearrangements without departing from the essential spirit thereof.

What is claimed is:

1. A combustion apparatus, comprising

a. means for vaporizing fuel, including means for introducing fuel into said vaporizing means for vaporization thereof;

b. mixing means downstream of said vaporizing means for mixing air with said vaporized fuel, said mixing means communicating with said vaporizing means for flow of vaporized fuel thereto, and means for flowing air into said mixing means, said mixing means being operable to mix said air and said vaporized fuel without combustion thereof;

c. combustion means downstream of said mixing means for combusting said mixture of air and vaporized fuel, including ignitor and flame-holding means for igniting said mixture of air and vaporized fuel to form a flame; and

d. said mixing means including means for passing said mixture of air and vaporized fuel from said mixing means to said combustion means at a velocity in ex-

cess of the flame propagation speed and said mixing means being of sufficient length to allow said air and vaporized fuel to be thoroughly mixed such that the mixing means delivers at said ignitor and flame-holding means a substantially uniform mixture of air and vaporized fuel on a molecular scale without prior combustion thereof.

2. A combustion apparatus as defined in claim 1 including means operable to deliver downstream from said ignitor and flame holder means for additional combustion a second mixture of air and vaporized fuel which mixture is substantially uniform on a molecular level.

3. A combustion apparatus as defined in claim 1 wherein said fuel vaporizing means communicates with a source of air and is of a configuration which enables preliminary combustion of a portion of the fuel introduced in said fuel vaporizing means to occur, said fuel vaporizing means including an ignitor operable to initiate said preliminary combustion.

4. A combustion apparatus as defined in claim 3 wherein said fuel vaporizing means and said mixing means communicate with a common source of air, the relative dimensions of said fuel vaporizing means and said mixing means being such that when the velocity of gases passing through said mixing means is in excess of the flame propagation speed, the velocity of gases passing through said fuel vaporizing means will be less than the flame propagation speed.

5. A combustion apparatus as defined in claim 4 including air restriction means disposed in said fuel vaporizing means for restricting the amount of air therein admitted to less than the stoichiometric amount required for the amount of fuel introduced in said fuel vaporizing means.

6. A combustion apparatus as defined in claim 4 including a secondary fuel injector disposed to deliver additional fuel into said fuel vaporizing means in an area in which such additional fuel will be vaporized by said preliminary combustion.

7. A combustion apparatus as defined in claim 1 wherein said fuel vaporizing means communicates with a source of gas of a temperature sufficient to completely vaporize fuel introduced in said fuel vaporizing means, and conduit means are provided to allow flow of said gas into said fuel vaporizing means.

8. A combustion apparatus as defined in claim 7 wherein said source of gas is the gaseous products formed upon combustion in said combustion means of said mixture of air and vaporized fuel at said ignitor and flame holding means.

9. A combustion apparatus as defined in claim 8 wherein said air compressor is also the means for flowing air into said mixing means.

10. A combustion apparatus as defined in claim 7 wherein said source of gas is a turbine air compressor.

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