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Quigg et al.

[11] **3,826,079**

[45] **July 30, 1974**

[54] **COMBUSTION METHOD WITH SELECTIVE COOLING AND CONTROLLED FUEL MIXING**

[75] Inventors: **Harold T. Quigg; Robert M. Schirmer,** both of Bartlesville, Okla.

[73] Assignee: **Phillips Petroleum Company,** Bartlesville, Okla.

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[21] Appl. No.: **208,247**

[52] **U.S. Cl.**..... **60/39.06,** 60/39.51, 60/39.65, 60/39.74, 431/10

[51] **Int. Cl.** **F02c 7/26**

[58] **Field of Search**..... 60/39.06, 39.02, 39.51, 60/39.65, 39.69, 39.74 R; 431/10

[56] **References Cited**

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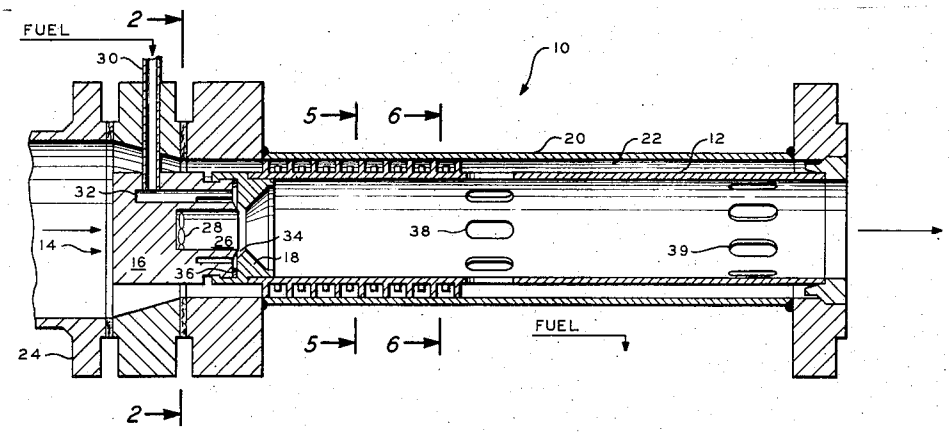
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Primary Examiner—Carlton R. Croyle
Assistant Examiner—Warren Olsen

[57] **ABSTRACT**

New combustors, and methods of operating same, which produce lower emissions, particularly lower emissions of nitrogen oxides. Method and means are provided for reducing the flame temperature in a primary combustion zone of said combustors.

6 Claims, 11 Drawing Figures



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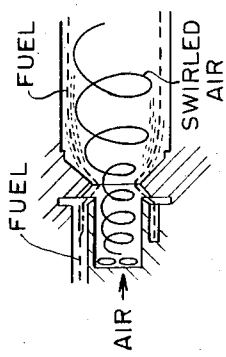


FIG. 1-A

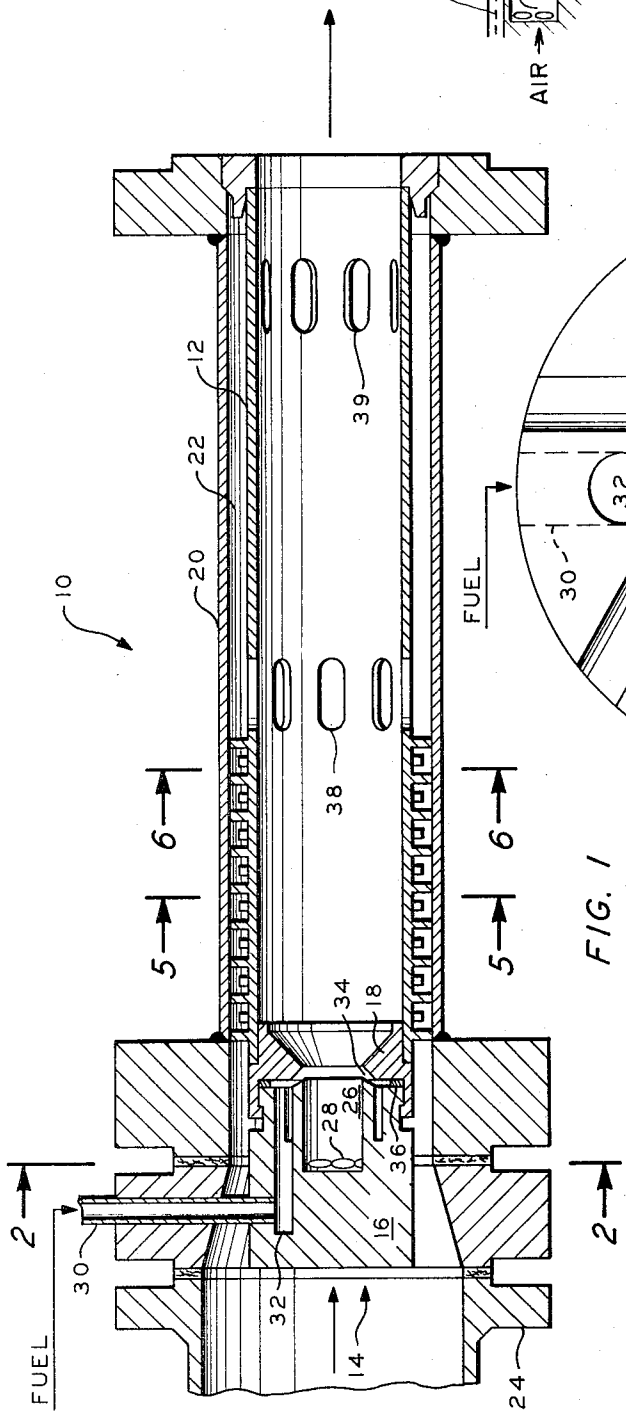


FIG. 1

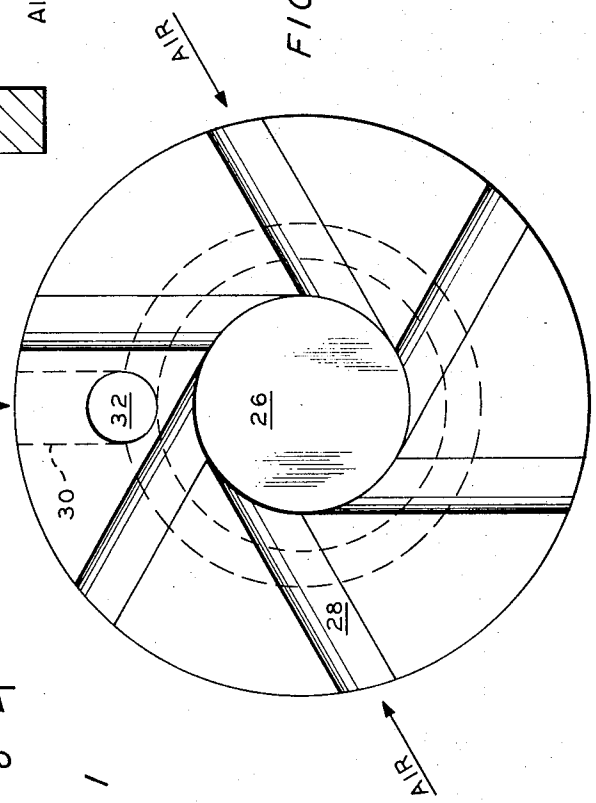


FIG. 2

INVENTORS
H.T. QUIGG
R.M. SCHIRMER

BY

Quigg and Oberlin

ATTORNEYS

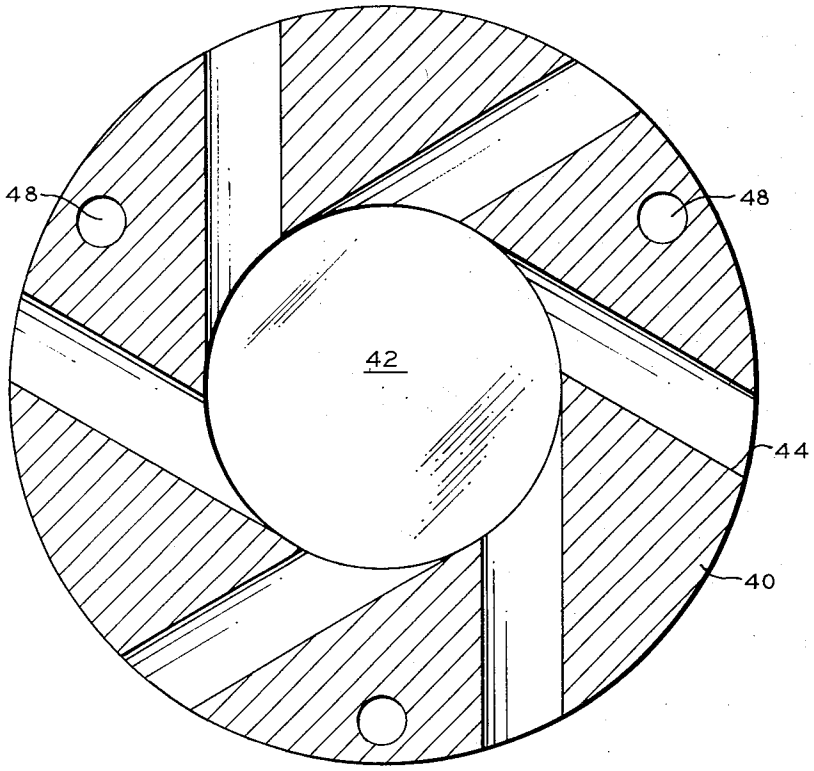


FIG. 4

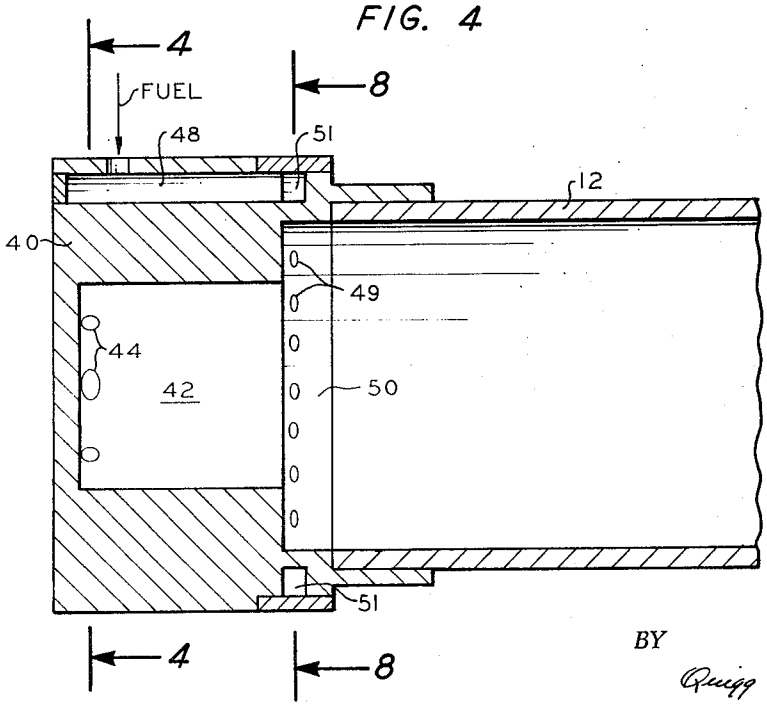


FIG. 3

INVENTORS
H.T. QUIGG
R.M. SCHIRMER

BY
Quigg and Oberlin

ATTORNEYS

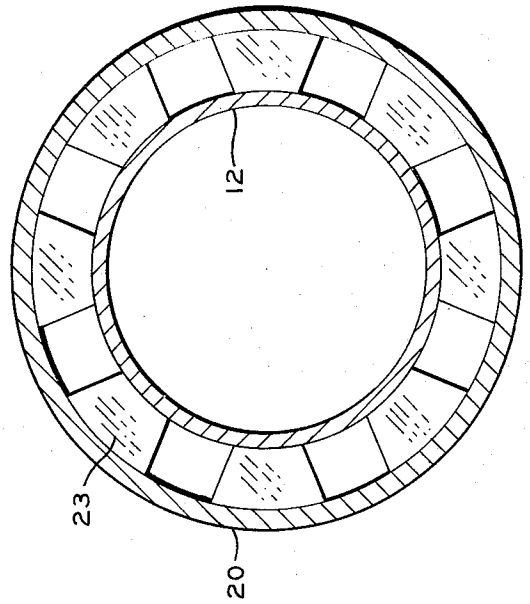


FIG. 5

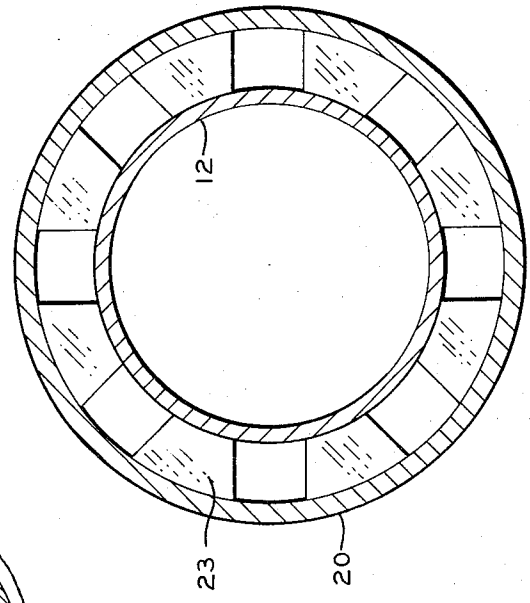


FIG. 6

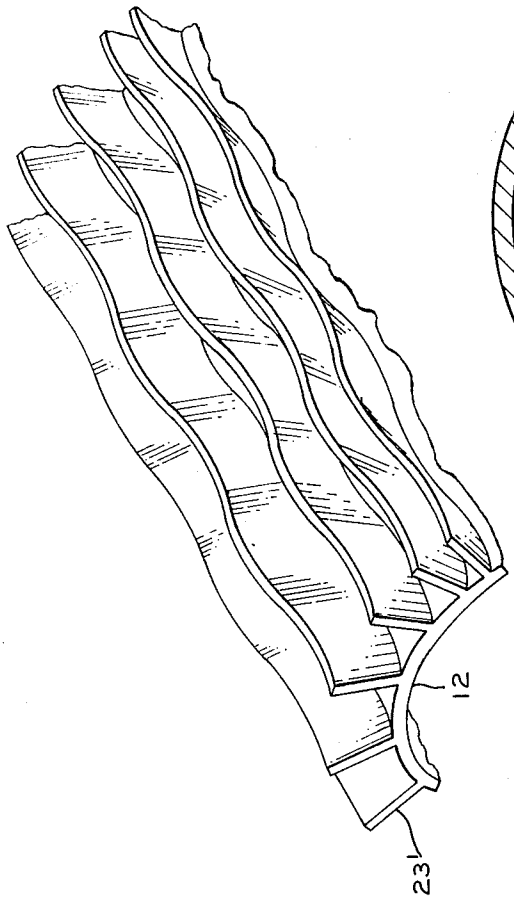


FIG. 7

INVENTORS
H. T. QUIGG
R. M. SCHIRMER

BY

Quigg and Oberlin

ATTORNEYS

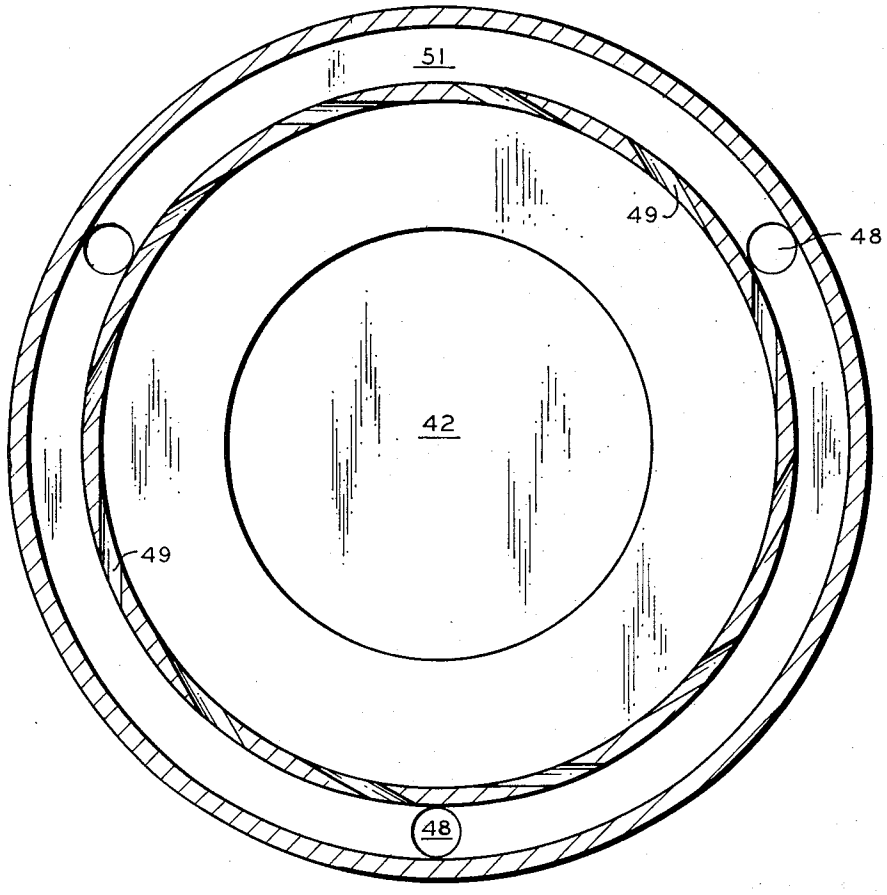


FIG. 8

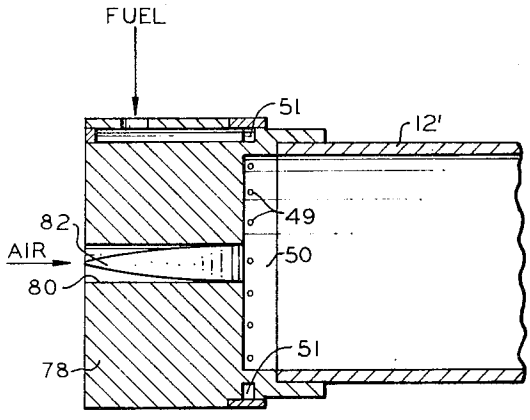


FIG. 9

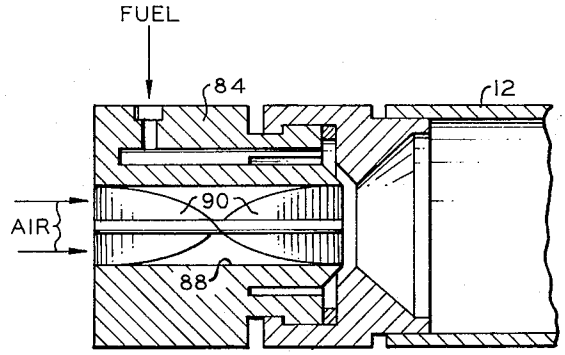


FIG. 10

INVENTOR.
H.T. QUIGG
R.M. SCHIRMER

BY

Quigg and Oberlin

ATTORNEYS

COMBUSTION METHOD WITH SELECTIVE COOLING AND CONTROLLED FUEL MIXING

This invention relates to improved gas turbine combustors and methods of operating same.

Air pollution has become a major problem in the United States and other highly industrialized countries of the world. Consequently, the control and/or reduction of said pollution has become the object of major research and development effort by both governmental and nongovernmental agencies. Combustion of fossil fuel is a primary source of said pollution. It has been alleged, and there is supporting evidence, that automobiles employing conventional piston-type engines are a major contributor to said pollution. Vehicle emission standards have been set by the United States Environmental Protection Agency which are sufficiently restrictive to cause automobile manufacturers to consider employing alternate engines instead of the conventional piston engine.

The gas turbine engine is being given serious consideration as an alternate engine. However, insofar as we presently know, there is no published information disclosing realistic and/or practical combustors which can be operated at conditions typical of those existing in high performance engines, and which will have emission levels meeting or reasonably approaching the standards set by said United States Environmental Protection Agency. This is particularly true with respect to nitrogen oxides emissions.

Thus, there is a need for a combustor of practical and/or realistic design which can be operated in a manner such that the emissions therefrom will meet said standards. Even a practical combustor giving reduced emissions (compared to the combustors of the prior art) approaching said standards would be a great advance in the art. Such a combustor would have great potential value because it is possible the presently very restrictive standards may be relaxed.

The present invention solves the above-described problems by providing improved combustors, and methods of operating same, which produce emissions meeting or reasonably approaching the present stringent standards established by said Environmental Protection Agency. Said methods comprise a combination of (a) controlled mixing of fuel and air within the flame tubes of said combustors, and (b) reduction of the flame temperature within said flame tubes.

Thus, according to the invention, there is provided a combustor, comprising, in combination an outer casing; a flame tube disposed concentrically within said casing and spaced apart therefrom to form an annular chamber between said flame tube and said casing; a plurality of fins extending from the external surface of said flame tube into said annular chamber; air inlet means for introducing a swirling stream of air into the upstream end portions of said flame tube; and fuel inlet means for introducing a stream of fuel into said flame tube in a direction which is from tangent to less than perpendicular, but non-parallel, to the periphery of said stream of air.

Further according to the invention, there is provided a method for reducing the formation of nitrogen oxides formed in the combustion of a fuel in a combustor, which method comprises: introducing a swirling stream of air into the upstream end portion of a combustion zone; forming and introducing an annular stratum of said fuel around said stream of air and in a direction which is from tangent to less than perpendicular, but non-parallel, to the periphery of said stream of air so as to effect controlled mixing of said fuel and air at the interface therebetween; burning said fuel; and decreasing the flame temperature within said combustion zone by removing heat from an extended outer wall surface of said combustion zone.

FIG. 1 is a view in cross section of a combustor in accordance with the invention.

FIG. 1-A is a schematic representation of fuel and air introduction in accordance with the invention.

FIG. 2 is a cross section taken along the line 2—2 of FIG. 1.

FIG. 3 is a view in cross section of a portion of the flame tube and a closure member therefor of another combustor in accordance with the invention. The outer housing or casing and other elements of this combustor is substantially like that shown in FIG. 1.

FIG. 4 is a view in cross section taken along the line 4—4 of FIG. 3.

FIG. 5 is a view in cross section taken along the line 5—5 of FIG. 1.

FIG. 6 is a view in cross section taken along the line 6—6 of FIG. 1.

FIG. 7 is a perspective view of a portion of a flame tube showing an alternate type of fin which can be employed.

FIG. 8 is a view in cross section taken along the line 8—8 of FIG. 3.

FIGS. 9 and 10 are views in cross section of other closure members or dome members which can be employed with the flame tubes of the other combustors described herein.

Referring now to the drawings wherein like reference numerals are employed to denote like elements, the invention will be more fully explained.

In FIG. 1 there is illustrated a combustor in accordance with the invention, denoted generally by the reference numeral 10, which comprises a flame tube 12. Said flame tube 12 is open at its downstream end, as shown, for communication with a conduit leading to a turbine or other utilization of the combustion gases. A closure member, designated generally by the reference numeral 14, is provided for closing the upstream end of said flame tube. Said closure member can be fabricated integrally, i.e., as one element, if desired. However, it is presently preferred to fabricate said closure member 14 as two or more elements, e.g., an upstream element 16 and a downstream element 18. An outer casing 20 is disposed concentrically around said flame tube 12 and said closure member 14 and is spaced apart therefrom to form an annular chamber 22 around said flame tube and said closure member. Said annular chamber 22 is closed at its downstream end by any suitable means such as that illustrated. A plurality of fins 23, or other type of turbulators, extend from the outer surface of said flame tube 12 into said annular space 22. Preferably, said fins are provided on said flame tube in the region between the downstream end portion of said closure member and the first set of openings 38. However, it is within the scope of the invention to provide fins essentially the full length of flame tube 12, e.g., to openings 39. As shown in FIGS. 1, 5, and 6, said fins are arranged in alternate spaced apart rows around said flame tube and are spaced apart from each other in each row. Said fins can extend from flame tube 12 into annular space 22 any convenient and suitable distance,

but preferably extend the full distance to outer casing **20**, as shown. FIG. **7** illustrates an alternate type of longitudinal fin **23'** which can be employed if less pressure drop in annular space **22** is desired. Said fins **23** and **23'** thus form an extended surface on the outer wall of flame tube **12**. Any other suitable type of fin or extended surface can be employed.

Suitable flange members, as illustrated, are provided at the downstream end of said flame tube **12** and outer housing **20** for mounting same and connecting same to a conduit leading to a turbine or other utilization of the combustion gases from the combustor. Similarly, suitable flange members are provided at the upstream end of said flame tube **12** and said outer housing **20** for mounting same and connecting same to a conduit **24** which leads from a compressor or other source of air. While not shown in the drawing, it will be understood that suitable support members are employed for supporting said flame tube **12** and said closure member **14** in the outer housing **20** and said upstream end flange members. Said support members have been omitted so as to simplify the drawing.

A generally cylindrical swirl chamber **26** is formed in said upstream element **16** of closure member **14**. The downstream end of said swirl chamber **26** is in open communication with the upstream end of said flame tube **12**. A first air inlet means is provided for introducing a swirling mass of air into the upstream end portion of said swirl chamber **26** and then into the upstream end of said flame tube. As illustrated in FIGS. **1** and **2**, said air inlet means comprises a plurality of air conduits **28** extending into said swirl chamber **26** tangentially with respect to the inner wall thereof. Said conduits **28** extend from said annular passageway or chamber **22** into said swirl chamber **26**.

A fuel inlet means is provided for introducing a stream of fuel in a direction which is from tangent to less than perpendicular, but non-parallel, to the periphery of said stream of air. As illustrated in FIGS. **1** and **2**, said fuel inlet means comprises a fuel conduit **30** leading from a source of fuel, communicating with a passageway **32**, which in turn communicates with fuel passageway **34** which is formed by an inner wall of said downstream element **18** of closure member **14** and the downstream end wall of said upstream element **16** of closure member **14**. It will be noted that the inner wall of said downstream element is spaced apart from and is complementary in shape to the downstream end wall of said upstream element **16**. The direction of the exit portion of said fuel passageway **34** can be varied over a range which is intermediate or between tangent and perpendicular, but non-parallel, to the periphery of the stream of air exiting from swirl chamber **26**. Varying the direction of the exit portion of fuel passageway **34** provides one means or method for controlling the degree of mixing between the fuel stream and said air stream at the interface therebetween. As illustrated in FIG. **1**, the direction of the exit portion of fuel passageway **34** forms an angle of approximately 45° with respect to the periphery of the air exiting from swirl chamber **26**. Generally speaking, in most instances, it will be desired that the exit portion of said fuel passageway **34** has a direction which forms an angle within the range of from about **15°** to about 75°, preferably about **30°** to about 60° with respect to the periphery of the stream of air exiting from swirl chamber **26**. In most instances, it will be preferred that the fuel from fuel passageway **34** be introduced in a generally downstream direction. However, it is within the scope of the invention to introduce said fuel in an upstream direction. Shim **36** provides means for varying the width of said fuel passageway **34**. Any other suitable means, such as threads provided on the walls of upstream element **16** and downstream element **18**, can be provided for varying the width of said fuel passageway **34**. As will be understood by those skilled in the art in view of this disclosure, the shape of the upstream inner wall of said downstream element **18** and the shape of the downstream end wall of said upstream element **16** can be changed, but maintained complementary with respect to each other, so as to accommodate the above-described changes in direction and width of said fuel passageway **34**.

A plurality of openings **38** is provided at a first station located in the downstream portion of said flame tube **12** for admitting a second stream of air into said flame tube from said annular chamber **22**. Preferably, a second plurality of openings **39** is provided at a second station downstream and spaced apart from said openings **38** for admitting a third stream of air into said flame tube from said annular chamber **22**. When only one set of openings such as **38** is provided, said second stream of air will comprise principally quench air for quenching the combustion products before passing same on to the turbine. When two sets of openings such as **38** and **39** are provided, said second stream of air will comprise principally secondary air, and said third stream of air will comprise principally quench air. Varying the distance between said openings **38** and **39** provides a method of controlling carbon monoxide emissions. Generally speaking, increasing said distance will decrease carbon monoxide emissions.

Referring now to FIG. **3**, there is illustrated a portion of the flame tube and a closure member therefor of another combustor in accordance with the invention. It will be understood that the complete combustor will comprise an outer housing or casing **20** and suitable flange members substantially like that illustrated in FIG. **1**. The flame tube **12** of the combustor of FIG. **3** is like flame tube **12** of FIG. **1**. A closure member **40** is mounted on the upstream end of said flame tube **12** in any suitable manner so as to close the upstream end of said flame tube except for the openings provided in said closure member. A generally cylindrical swirl chamber **42** is formed in said closure member **40**. The downstream end of said swirl chamber is in open communication with the upstream end of said flame tube. An air inlet means is provided for introducing a swirling mass of air into the upstream end portion of said swirl chamber **42** and then into the upstream end of said flame tube **12**. As illustrated in FIGS. **3** and **4**, said air inlet means comprises a plurality of air conduits **44** extending into said swirl chamber **42** tangentially with respect to the inner wall thereof. Said conduits **44** extend from an annular chamber **22**, similarly as in FIG. **1**. The fuel inlet means in the combustor of FIG. **3** comprises a fuel supply conduit **46** which is in communication with three fuel passageways **48**, which in turn is in communication with an annular fuel passageway **51** formed in the downstream end portion of said closure member **40**. A plurality of fuel conduits **49** extend from said passageway **51** into a recess **50** formed in the downstream end portion of said closure member, and tangentially with respect to the inner wall of said recess. As illus-

trated in FIGS. 3 and 4, said air inlet conduits 44 are adapted to introduce air tangentially into swirl chamber 42 in a clockwise direction (when looking downstream), and said fuel inlet conduits 49 in FIG. 8 are adapted to introduce fuel tangentially into said recess 50 in a counterclockwise direction. This is a presently preferred arrangement in one embodiment of the invention. However, it is within the scope of the invention to reverse the directions of said air inlet conduits 44 and said fuel inlet conduits 49, or to have the directions of both said air inlet conduits and said fuel inlet conduits the same, e.g., both clockwise or both counterclockwise.

Referring now to FIGS. 9 and 10, there are illustrated other types of closure members which can be employed with the flame tubes of the combustors described above. In FIG. 9 closure member 78 is similar to closure member 40 of FIG. 3. The principal difference is that in closure member 78 a conduit means 80 is provided which extends through said closure member 78 into communication with the upstream end portion of flame tube 12, for example. At least one swirl vane 82 is positioned in said conduit means 80 for imparting a swirling motion to the air passing through said conduit means 80. In FIG. 10, closure member 84 is similar to closure member 14 of FIG. 1. The principal difference is that in closure member 84 an annular conduit means 88 is provided which extends through the body of said closure member 84 into open communication with the upstream end of the flame tube 12, for example. At least one swirl vane 90 is provided in said conduit means 88 for imparting a swirling motion to the air passing through said conduit 88.

In one presently preferred method of operating the combustor of FIG. 1, a stream of air from a compressor (not shown) is passed via conduit 24 into annular space 22. A portion of said air then passes through tangential conduits 28 into swirl chamber 26. Said tangential conduits 28 impart a helical or swirling motion to the air entering said swirl chamber and exiting therefrom. This swirling motion creates a vortex action resulting in a reverse circulation of hot gases within flame tube 12 upstream toward said swirl chamber 26 during operation of the combustor.

A stream of fuel, preferably prevaporized, is admitted via conduit 30, passageway 32, and fuel passageway 34. Fuel exiting from fuel passageway 34 is formed into an annular stratum around the swirling stream of air exiting from swirl chamber 26. This method of introducing fuel and air effects a controlled mixing of said fuel and air at the interface therebetween. Initial contact of said fuel and air occurs upon the exit of said air from said swirl chamber 26. Immediately after said initial contact the fuel and air streams (partially mixed at said interface) are expanded, in a uniform and graduated manner during passage of said fuel and air through the flared portion of member 18, from the volume thereof in the region of said initial contact to the volume of said combustion chamber at a point in said flame tube downstream from said initial contact. Said expansion of fuel and air thus takes place during at least a portion of the mixing of said fuel and said air. The resulting mixture of fuel and air is burned and combustion gases exit the downstream end of flame tube 12. A second stream of air, comprising secondary air, is admitted to the interior of flame tube 12 from annular space 22 via inlet openings 38 in the downstream portion of said flame tube. A third stream of air, comprising quench air, is admitted to the interior of flame tube 12 from annular space 22 via inlet openings 39. Said second and third streams of air in passing over fins 23 in annular space 22 extract heat from said fins (and the interior of flame tube 12) and thus reduce the flame temperature in said flame tube.

In one presently preferred method of operating the combustor of FIG. 3, the method of operation is similar to that described above for the combustor of FIG. 1. A stream of air is admitted to swirl chamber 42 via tangential inlet conduits 44 which impart a helical or swirling motion to said air. A stream of fuel, preferably prevaporized, is admitted via conduit 46, fuel passageways 48, and tangential fuel conduits 49 into recess 50 formed at the downstream end of said closure member 40. Said fuel is thus formed into an annular stratum around the swirling stream of air exiting from swirl chamber 42. This method of introducing fuel and air also effects controlled mixing of said fuel and air at the interface therebetween. The remainder of the operation is essentially as described for the combustor of FIG. 1.

The following examples will serve to further illustrate the invention.

EXAMPLES

As series of test runs was made employing a combustor of the invention described herein, and a typical "standard" or prior art combustor as a control combustor. The same fuel was used in all of said test runs. Properties of said fuel are set forth in Table I below. Design details of the combustor of the invention are set forth in Table II below. Said design details, e.g., dimensions, are given by way of illustration only and are not to be construed as limiting on the invention. Said dimensions can be varied within wide limits so long as the improved results of the invention are obtained. For example, the formation of nitrogen oxides in a combustion zone is an equilibrium reaction. Thus, in designing a combustion zone, attention should be given to the size thereof so as to avoid unduly increasing the residence time therein. It is desirable that said residence time not be long enough to permit the reactions involved in the formation of nitrogen oxides to attain equilibrium.

Said control combustor basically embodies the principal features of combustors employed in modern aircraft-turbine engines. It is a straight-through can-type combustor employing fuel atomization by a single simplex-type nozzle. The combustor liner was fabricated from 2-inch pipe, with added internal deflector skirts for air film cooling of surfaces exposed to the flame. Exhaust emissions from this combustor, when operated at comparable conditions for combustion, are in general agreement with measurements presently available from several different gas turbine engines. Said control combustor had dimensions generally comparable to the above described combustors of the invention.

The combustor of the invention and said control combustor were run at 12 test points or conditions, i.e., 12 different combinations of inlet-air temperature, combustor pressure, flow velocity, and heat input rate. Test points or conditions 1 to 6 simulate idling conditions, and test points 7 to 12 simulate maximum power conditions. The combustor of the invention was run

using prevaporized fuel. The control combustor was run using atomized liquid fuel. In all runs the air stream to the combustors was preheated by conventional means. Analyses for content of nitrogen oxides (reported as NO), carbon monoxide, and hydrocarbons (reported as carbon) in the combustor exhaust gases were made at each test condition for each combustor. The method for measuring nitrogen oxides was based on the Saltzman technique, Analytical Chemistry 26, No. 12, 1954, pages 1,949–1,955. Carbon monoxide was measured by a conventional chromatographic technique. Hydrocarbon was measured by the technique described by Lee and Wimmer, SAE Paper 680769. Each pollutant measured is reported in terms of pounds per 1,000 pounds of fuel fed to the combustor. The results from test conditions 1 to 6 are set forth in Table III below. The results from test conditions 7 to 12 are set forth in Table IV below.

TABLE I

PHYSICAL AND CHEMICAL PROPERTIES OF TEST FUEL

	Philjet A-50
ASTM Distillation, °F.	
Initial Boiling Point	340
5 vol % evaporated	359
10 vol % evaporated	362
20 vol % evaporated	371
30 vol % evaporated	376
40 vol % evaporated	387
50 vol % evaporated	398
60 vol % evaporated	409
70 vol % evaporated	424
80 vol % evaporated	442
90 vol % evaporated	461
95 vol % evaporated	474
End Point	496
Residue, vol %	0.8
Loss, vol %	0.0
Gavity, degrees API	46.6
Density, lb/gal.	6.615
Heat of Combustion, net, Btu/lb.	18,670
Hydrogen Content, wt %	14.2
Smoke Point, mm	27.2
Sulfur, wt %	0.001
Gum, mg/100 ml	0.0
Composition, vol %	
Paraffins	52.8
Cycloparaffins	34.5
Olefins	0.1
Aromatics	12.6
Formula (calculated)	$(C_{11}H_{22})$
Stoichiometric Fuel/Air Ratio, lb/lb	0.0676

TABLE II

COMBUSTOR DESIGN

Variable	Invention Combustor
Closure Member (14)	
Air Inlet Diameter, in.	0.875
Inlet Type	Tangent
Hole Diameter, in.	0.188
Number of Holes	6
Total Hole Area, sq. in.	0.166
% Total Combustor Hole Area	3.213
Fuel Slot, in.	0.005
Flame Tube (12)	
1st Station (38)	
Hole Diameter, in.	5/16×1 *
Total Number of Holes	8
Total Hole Area, sq. in.	2.500
% Total Combustor Hole Area	48.393
2nd Station (39)	
Hole Diameter, in.	5/16—1
Total Number of Holes	8
Total Hole Area, sq. in.	2.500
% Total Combustor Hole Area	48.393
Combustor Cross Sect. Area, sq. in.	3.355
Total Combustor Hole Area, sq. in.	5.166
% Cross Sectional Area	153.933
Combustor Diameter, in.	2.067
Primary Zone Length, in.	3.375
Volume, cu. in.	11.326
Combustor Length, in.	11.250
Volume, cu. in.	37.751

*Holes are 5/16" diameter at ends; slots are 1" long. Cooling fins were 1/8" high.

TABLE III.—COMPARISON OF EMISSIONS FROM COMBUSTORS AT IDLE CONDITIONS

	Test conditions, lbs./1,000 lbs. fuel					
	1	2	3	4	5	6
Combustor operating variables:						
Temperature, inlet air, F.	900	900	900	900	900	900
Pressure, in. Hg abs.	50	50	50	50	50	50
Velocity, cold flow, ft/sec	250	250	250	400	400	400
Heat-input rate, Btu/lb. air	200	275	350	200	275	350
NITROGEN OXIDES:						
Combustors:						
Control combustor	3.4	3.4	3.2	2.2	2.1	2.3
Invention combustor	1.8	1.6	2.6	2.0	2.2	1.9
CARBON MONOXIDE:						
Combustors:						
Control Combustor	10	2	0	17	9	0
Invention combustor	5	4	0	5	14	3
HYDROCARBONS:						
Combustors:						
Control combustor	0.6	0.7	0.4	0.9	0.4	0.8
Invention combustor	0.4	0.4	0.2	0.4	2.2	0.6

TABLE IV.—COMPARISON OF EMISSIONS FROM COMBUSTORS AT MAXIMUM POWER CONDITIONS

	Test conditions, lbs./1,000 lbs. fuel					
	7	8	9	10	11	12
Combustor operating variables:						
Temperature, inlet air, F.	1,100	1,100	1,100	1,100	1,100	1,100
Pressure, in. Hg abs.	110	110	110	110	110	110
Velocity, cold flow, ft/sec.	250	250	250	400	400	400
Heat-input rate, Btu/lb. air	150	225	300	150	225	300
NITROGEN OXIDES:						
Combustors:						
Control combustor	10.7	11.2	10.0	9.9	8.0	7.4
Invention combustor	5.1	4.2	7.1	6.7	4.2	5.0
CARBON MONOXIDE:						
Combustors:						
Control combustor	0	0	0	0	0	0
Invention combustor	0	0	0	0	0	0
HYDROCARBONS:						
Combustors:						
Control combustor	0.2	0.1	0.2	0.2	0.2	0.2
Invention combustor	1.0	0.3	0.2	0.4	0.2	0.1

Referring to the above Table III, the data there given clearly show that the combustor of the invention gave results superior to the results obtained with the control combustor. The invention combustor gave superior results at substantially all test conditions with respect to nitrogen oxides emissions, the pollutant most difficult to control. Said data also show that combustors in accordance with the invention can be operated at idle conditions to give not more than about 2.5, preferably not more than 2 pounds of nitrogen oxides emissions per 1,000 pounds of fuel burned, and not more than about 5 pounds of nitrogen oxides emissions per 1,000 pounds of fuel burned at maximum power conditions.

In the examples, the fuel to the combustor of the invention was prevaporized. However, the invention is not limited to using prevaporized fuels and it is within the scope of the invention to employ atomized liquid fuels. For comparison purposes, all the runs set forth in the above examples were carried out under the conditions of inlet air temperature, combustor pressure, flow velocity, and heat input rate set forth in Tables III and IV. The invention is not limited to the values there given for said variables. It is within the scope of the invention to operate the combustors of the invention under any conditions which give the improved results of the invention. For example, it is within the scope of the invention to operate said combustors at inlet air temperatures within the range of from ambient temperatures or lower to about 1,500°F. or higher; at combustor pressures within the range of from about 1 to about 40 atmospheres or higher; at flow velocities within the range of from about 1 to about 500 ft. per second or higher; and at heat input rates within the range of from about 30 to about 1,200 Btu per pound of air. Generally speaking, operating conditions in the combustors of the invention will depend upon where the combustor is employed. For example, when the combustor is employed with a high pressure turbine, higher pressures and higher inlet air temperatures will be employed in the combustor. Thus, the invention is not limited to any particular operating conditions.

The term "air" is employed generically herein and in the claims, for convenience, to include air and other combustion supporting gases.

While the invention has been described, in some instances, with particular reference to combustors employed in combination with gas turbine engines, the invention is not limited thereto. The combustors of the invention have utility in other applications, e.g., boilers and other stationary power plants.

Thus, while certain embodiments of the invention have been described for illustrative purposes, the invention is not limited thereto. Various other modifications or embodiments of the invention will be apparent to those skilled in the art in view of this disclosure. Such modifications or embodiments are within the spirit and scope of the disclosure.

We claim:

1. A method for reducing the formation of nitrogen oxides formed in the combustion of a fuel in a combustor, which method comprises:
   - introducing a swirling stream of air into the upstream end portion of a combustion zone as the sole stream of primary air introduced into said combustion zone;
   - forming and introducing an annular stratum of said fuel around said stream of air by introducing said fuel in a direction toward and which is from tangent to less than perpendicular, but non-parallel, to the outer periphery of said stream of air so as to effect controlled mixing of said fuel and air at the interface to produce an annular fuel-air mixture;
   - passing said fuel-air mixture into said combustion zone as the sole fuel and air supplied to the upstream portion of said combustion zone;
   - burning said fuel; and
   - decreasing the flame temperature within said combustion zone by removing heat from an extended outer wall surface of said combustion zone.

2. A method according to claim 1 wherein said fuel and said air are expanded during at least a portion of said mixing thereof, and said expansion of said fuel and said air is initiated immediately after the initial contact at said interface therebetween.

3. A method according to claim 2 wherein:
   - said stream of air is initially introduced into a swirl zone having a diameter less than the diameter of said combustion zone;
   - said initial contact between said fuel and said air occurs upon the exit of said air from said swirl zone; and
   - said expansion of said fuel and said air occurs in a uniform and graduated manner from the volume thereof in the region of said initial contact to the

volume of said combustion chamber at a point in said combustion chamber downstream from said initial contact.

4. A method according to claim 3 wherein said fuel is introduced at an angle within the range of from about 15° to about 75° with respect to the outer periphery of said stream of air.

5. A method according to claim 1 wherein:

said flame temperature is reduced by passing a second stream of air over said extended outer wall surface of said combustion zone; and

said second stream of air is introduced into said combustion zone downstream from the point of introduction of said swirling stream of air.

6. A method according to claim 5 wherein a third stream of air is introduced into said combustion zone downstream from the point of introduction of said second stream of air.

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