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Quigg

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[54] **COMBUSTION PROCESS WITH SELECTIVE HEATING OF COMBUSTION AND QUENCH AIR**

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[21] Appl. No.: **238,318**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 208,245, Dec. 15, 1971, abandoned.

[52] **U.S. Cl.** **60/39.02**, 60/39.06, 60/39.51, 60/39.65, 431/10

[51] **Int. Cl.** **F02c 1/04**

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

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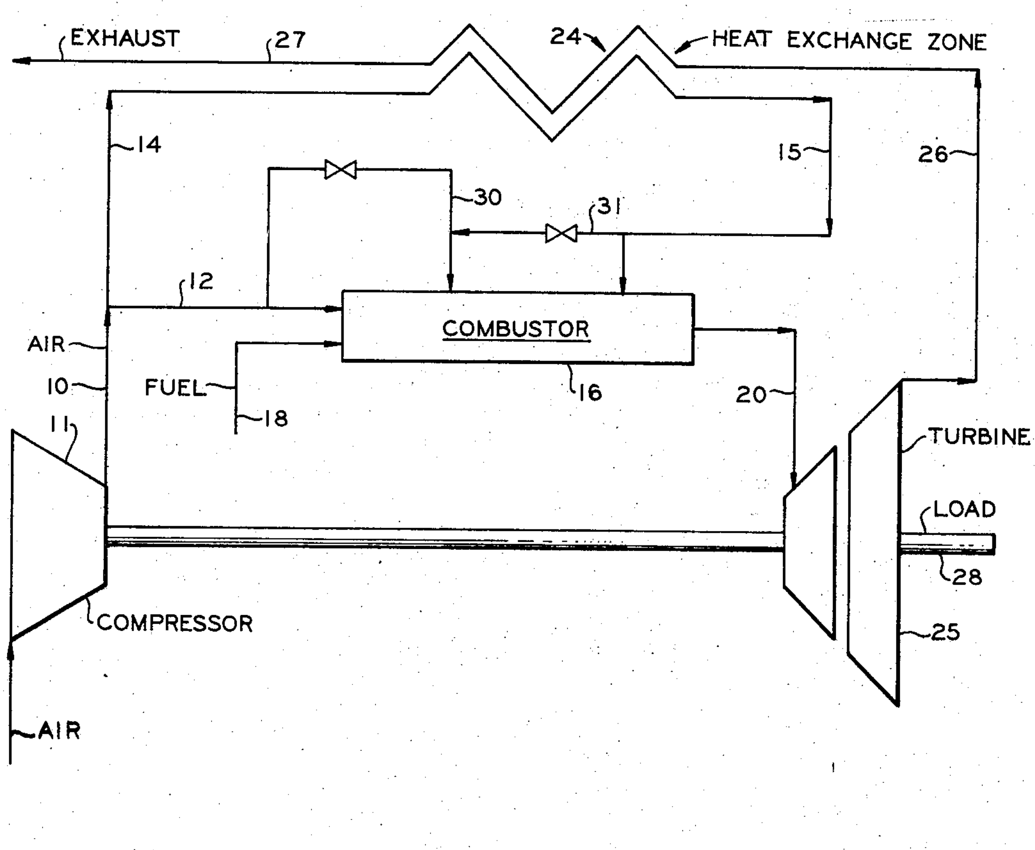
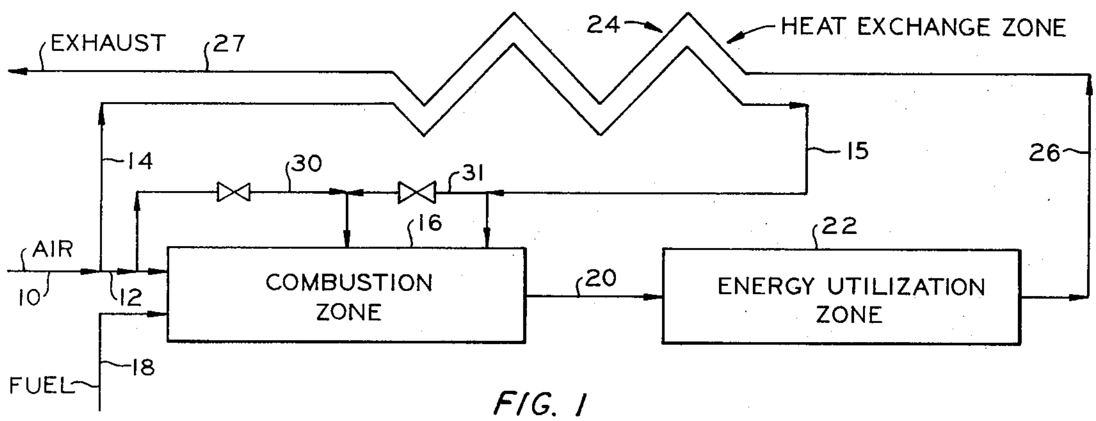
Assistant Examiner—Warren Olsen

[57] **ABSTRACT**

A new combustion process wherein combustion efficiency is retained while reducing inlet air temperature to the combustor so as to obtain reduced nitrogen oxides emissions. A new combustor, and a new combination of combustion apparatus and heat utilization apparatus are also provided.

22 Claims, 12 Drawing Figures




EXHAUST
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HEAT EXCHANGE ZONE
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AIR
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COMBUSTION ZONE
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ENERGY UTILIZATION ZONE
FUEL
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FIG. 1

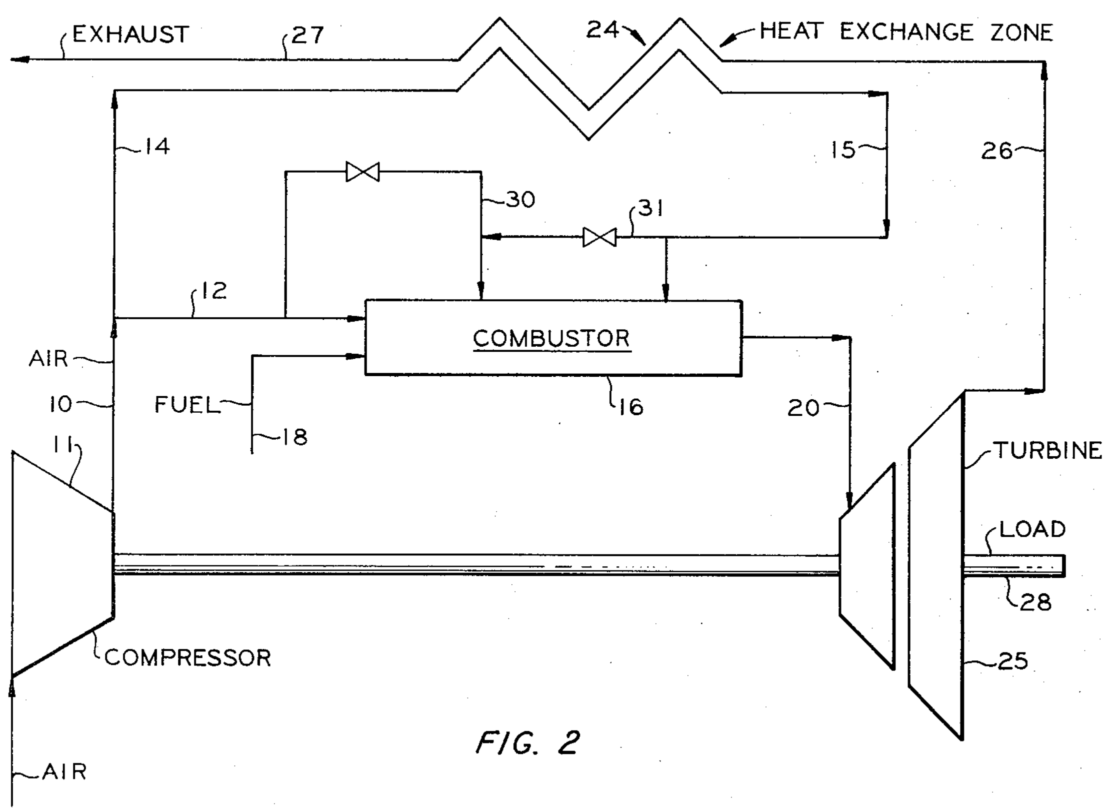
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FIG. 2

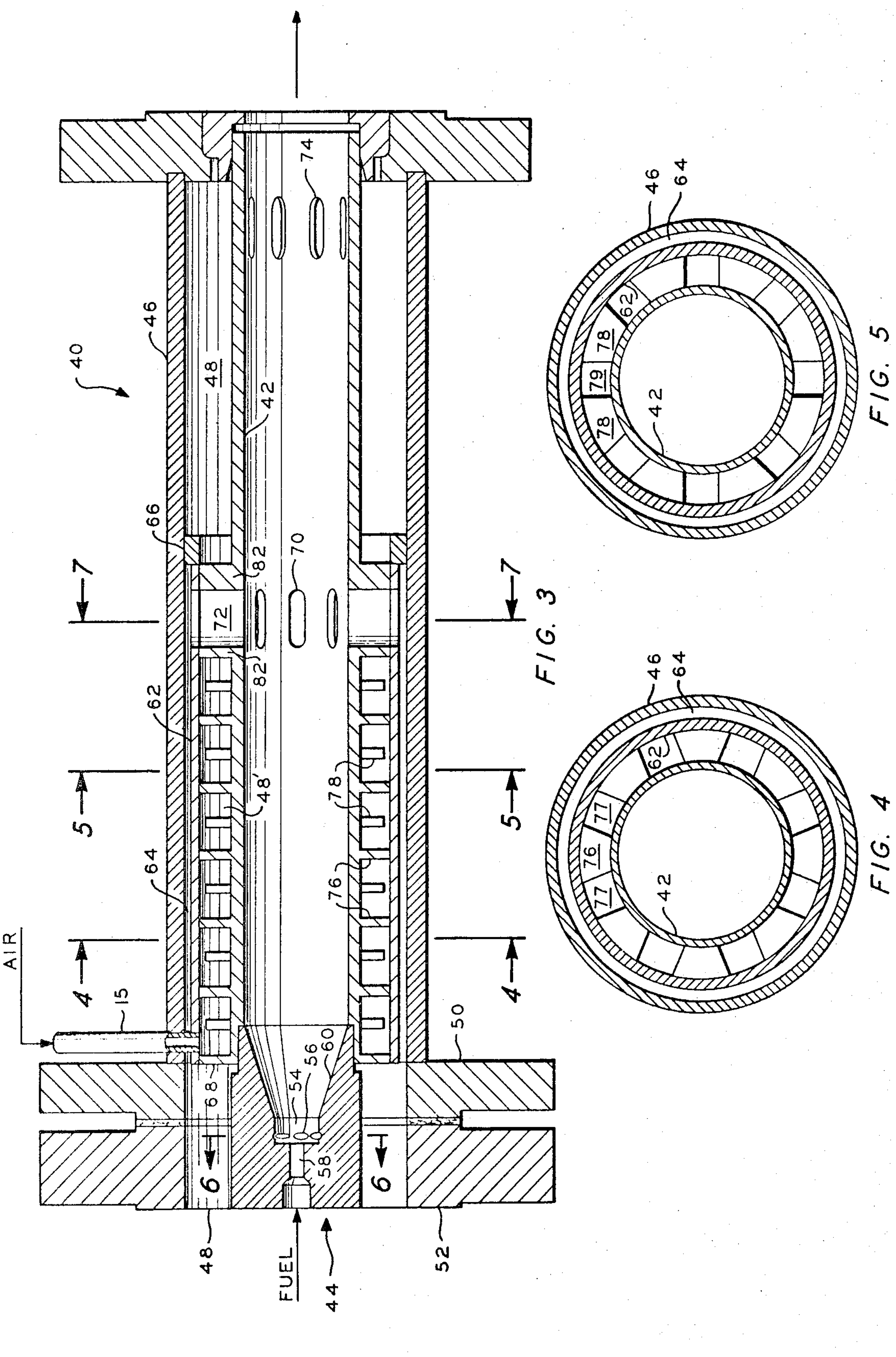

FIG. 3

FIG. 4

FIG. 5

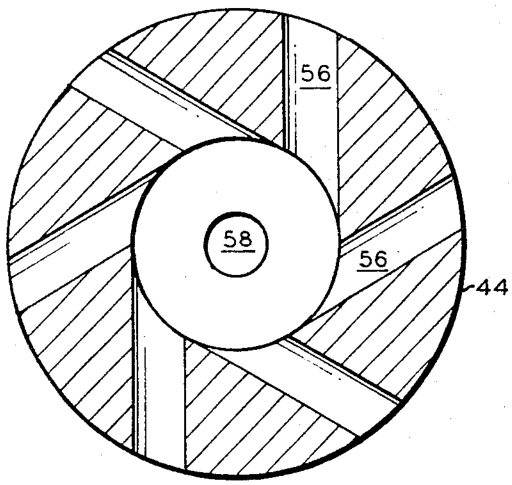

FIG. 6

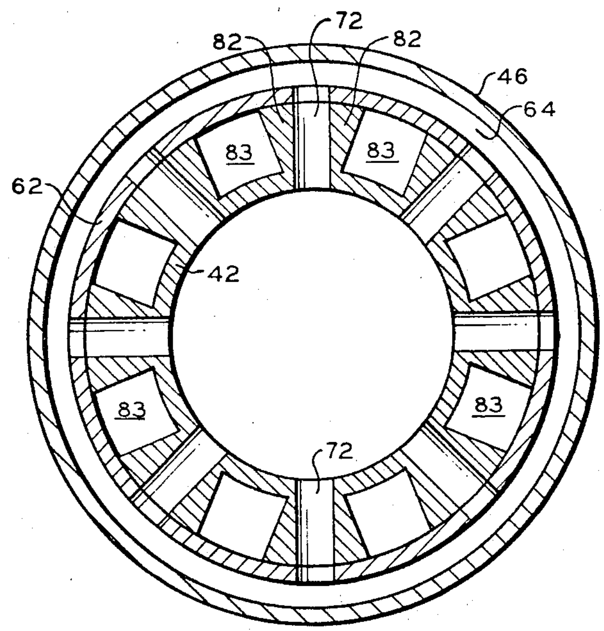

FIG. 7

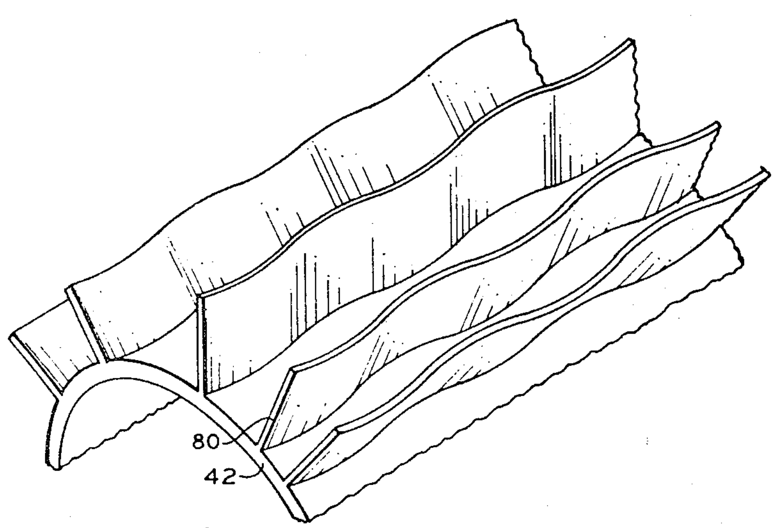

FIG. 8

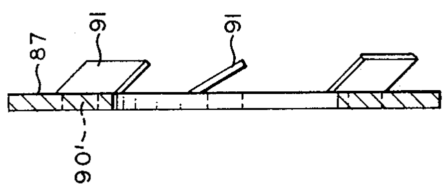

FIG. 11

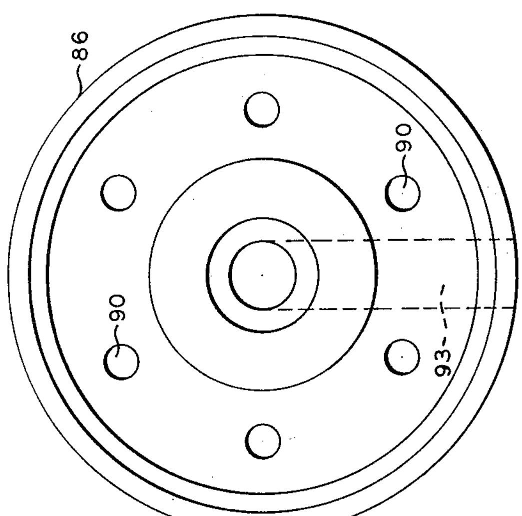

FIG. 10

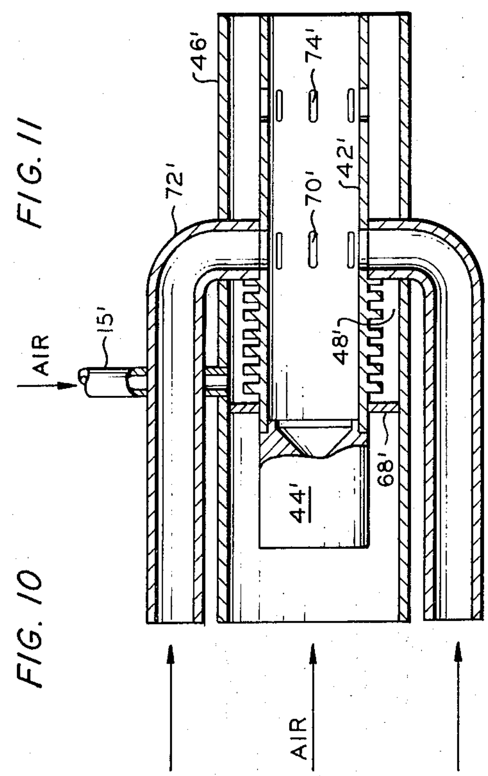

FIG. 12

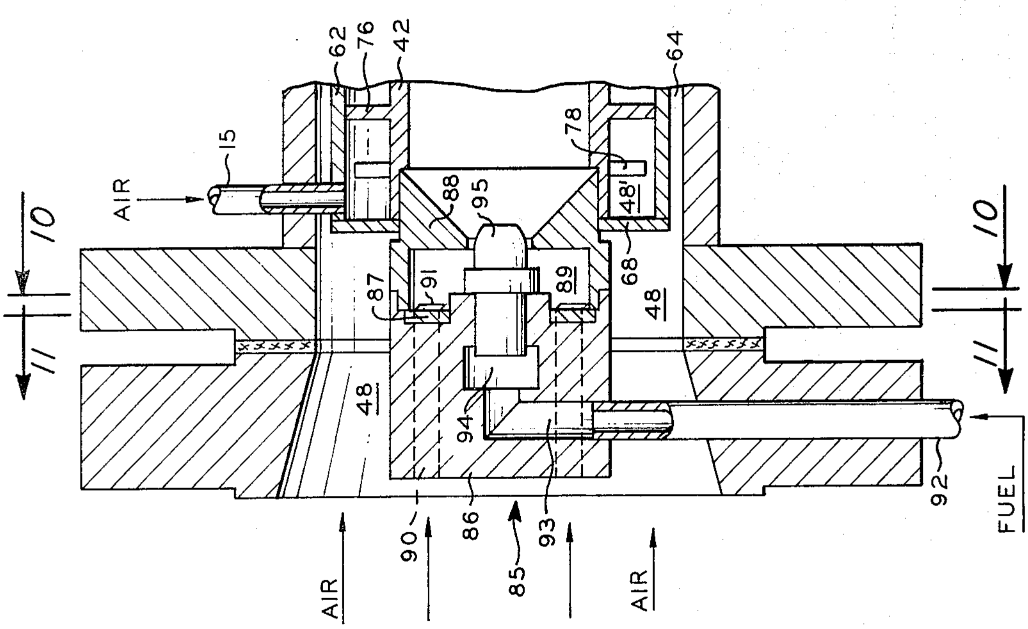

FIG. 9

COMBUSTION PROCESS WITH SELECTIVE HEATING OF COMBUSTION AND QUENCH AIR

This application is a continuation-in-part of copending application Ser. No. 208,245, filed Dec. 15, 1971, now abandoned.

This invention relates to improved combustion processes, improved combustors which can be employed in said processes, and an improved combination of combustion apparatus and heat utilization apparatus.

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 the automobiles employing conventional piston-type engines burning hydrocarbon fuels 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 is presently known, there is no published information disclosing realistic and/or practical combustion processes or 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 standard 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 combustion process, and 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 process and/or a combustor giving reduced emissions approaching said standards would be a great advance in the art. Such a process or combustor would have great potential value because it is possible the presently very restrictive standards may be reduced.

In the operation of combustion processes, conservation of the thermal energy produced is essential for efficiency. For example, in current gas turbine engines being proposed for automotive service, the turbine exhaust gases are heat exchanged with the inlet air to the primary combustion zone of the combustor so as to recover heat from said exhaust gases and improve overall efficiency. However, these engines will not meet the emission standards set by said Environmental Protection Agency.

The present invention solves the above-described problems by heatexchanging the turbine exhaust gases with another air stream to the combustor, e.g., the dilution or quench air, instead of the primary inlet air. The method of the invention thus provides for reducing the temperature of the primary inlet air to the combustor. This reduces the temperature in the combustor which results in reduced nitrogen oxides emissions. Thus, the overall advantageous result of the invention includes (1) reduction of nitrogen oxide emissions from the combustor while (2) maintaining thermal efficiency by returning the recovered heat to the process at a point where it has no effect on nitrogen oxides production. The invention also provides novel combustors, and a novel combination of combustion apparatus and heat utilization apparatus.

Thus, according to the invention there is provided in a method wherein a stream of air and a stream of fuel are passed to a combustion zone, at least partially mixed to form a combustible mixture which is burned to produce hot combustion gases containing heat energy, and said hot combustion gases are passed to a heat energy utilization zone to utilize a portion of said heat energy, the improvement comprising: dividing said stream of air into a first stream of air and a second stream of air; passing at least a portion of said first stream of air to said combustion zone; passing said second stream of air in heat exchange relationship with an exhaust stream from said heat energy utilization zone to heat said second stream of air and thereby utilize an additional portion of said energy; and passing at least a portion of said heated second stream of air into a quench region of said combustion zone.

Further according to the invention, there is provided an apparatus for producing and utilizing heat energy, comprising, in combination: an air supply conduit; a combustion means for burning a fuel to produce hot combustion gases containing heat energy; a fuel inlet means for introducing a fuel into said combustion means; a primary air conduit means connected to said air supply conduit and said combustion means for introducing a stream of air comprising primary air into said combustion means; a heat exchange means; a quench air conduit means connected to said air supply conduit, said heat exchange means, and said combustion means for delivering a stream of air comprising quench air from said air supply conduit, through said heat exchange means, and into said combustion means; a heat energy utilization means for utilizing a portion of said heat energy; an effluent conduit means for passing said hot combustion gases from said combustion means to said heat energy utilization means; and an exhaust conduit means connecting said heat energy utilization means and said heat exchange means for passing said hot combustion gases from said heat utilization means and into heat exchange relationship with said stream of quench air to heat said quench air and thereby utilize an additional portion of said heat energy.

Still further according to the invention, there is provided a combustor comprising, in combination: an outer tubular casing; a flame tube disposed concentrically within said casing and spaced apart therefrom to form a first annular chamber between said flame tube and said casing; an air inlet means for introducing a stream of air comprising primary air into the upstream end portion of said flame tube; a fuel inlet means for introducing fuel into the upstream end portion of said flame tube; an imperforate sleeve surrounding an upstream portion of said flame tube and spaced apart therefrom to longitudinally enclose an upstream portion of said first annular chamber and define a second annular chamber between said sleeve and said outer casing; a wall member closing the downstream end of said second annular chamber; a baffle member closing the upstream end of said enclosed portion of said first annular chamber; at least one opening provided in the wall of said flame tube at a first station located intermediate the upstream and downstream ends thereof; a first conduit means extending from said second annular chamber into communication with said opening located at said first station for admitting a second stream of air from said second annular chamber into the interior of said flame tube; at least one other opening provided in the wall of said flame tube at a second station located downstream from said first station for admitting a third stream of air from said first annular chamber into the interior of said flame tube; and a second conduit means extending through said outer casing, said second annular chamber, said sleeve, and into communication with said enclosed portion of said first annular chamber for admitting a stream of air thereto.

FIG. **1** is a diagrammatic flow sheet illustrating methods of producing and utilizing heat energy in accordance with the invention.

FIG. **2** is a diagrammatic illustration of methods and apparatus in accordance with the invention.

FIG. **3** is a view in cross section of a combustor in accordance with the invention.

FIG. **4**, **5**, **6**, and **7** are views in cross section taken along the lines **4—4**, **5—5**, **6—6**, and **7—7**, respectively, of FIG. **3.**

FIG. **8** is a fragmentary perspective view of a combustor flame tube illustrating another type of fin or extended surface which can be employed thereon.

FIG. **9** is a partial view in cross section of another combustor in accordance with the invention.

FIG. **10** is a front elevation view taken along the lines **10—10** of FIG. **9.**

FIG. **11** is a cross section view in elevation of the swirl plate of the dome or closure member in the combustor of FIG. **9.**

FIG. **12** is a diagrammatic view, partially in cross section of another combustor in accordance with the invention.

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** a stream of air from an air supply conduit **10** is divided into a first stream of air in conduit **12** and a second stream of air in conduit **14.** In one embodiment, at least a portion of said first stream of air **12** is passed into combustion zone **16.** A stream of fuel is introduced into said combustion zone via conduit **18.** Said combustion zone can comprise any suitable type of combustion zone for burning a mixture of fuel and air to produce hot combustion gases containing heat energy. For example, said combustion zone can be a combustor in a gas turbine engine, a combustor in an aircraft jet engine, a combustor or other furnace employed in a boiler for generating steam, or other types of stationary power plant, etc.

Said fuel and said first stream of air are at least partially mixed to form a combustible mixture which is burned to produce hot combustion gases containing heat energy. Said hot combustion gases are passed via conduit **20** to heat energy utilization zone **22** so as to utilize a portion of the heat energy in said gases. Said heat energy utilization zone can comprise any suitable method and/or means for utilizing or putting to use the heat energy contained in said hot combustion gases. For example, a turbine in a gas turbine engine wherein heat energy is converted to mechanical energy, or the heat exchange tubes in a boiler where water is connected to steam, etc.

Said second stream of air in conduit **14** is passed through heat exchange zone **24** in heat exchange relationship with an exhaust stream in conduit **26** from heat energy utilization zone **22** so as to heat said air and thereby utilize an additional portion of said heat energy. Said heat exchange zone can comprise any suitable method and/or means for effecting heat exchange between two separate streams of fluids, e.g., indirect heat exchange. The heated second stream of air is passed from said heat exchange zone via conduit **15** and returned to said combustion zone **16**, preferably at a downstream location therein, to serve as a diluent or quench medium to lower the temperature of the effluent gases in conduit **20** before they are passed to the heat energy utilization zone **22.**

In one preferred embodiment of the invention, said combustion zone **16** can comprise a primary combustion region, a secondary combustion region located downstream from said primary combustion region, and a quench or dilution region located downstream from said secondary combustion region. In this and other embodiments, said first stream of air in conduit **12** is further divided into a stream comprising primary air and another stream comprising secondary air. Said primary air is introduced into said primary combustion region and said secondary air is introduced into said secondary region via conduit **30.** At least a portion of said heated second stream of air is introduced into said quench or dilution region via conduit **15,** as before.

In another preferred embodiment of the invention, a portion of said heated second stream of air in conduit **15** can be passed via conduit **31** into conduit **30** for mixing with and increasing the temperature of the secondary air therein. The valves in said conduits **30** and **31** can be employed to regulate the relative proportions of the two streams of air.

FIG. **2** illustrates one embodiment of the invention wherein the effluent gases from combustor **16** are passed via conduit **20** to a turbine **25.** In turbine **25** a portion of the heat energy in said gases is converted to mechanical energy to drive shaft **28** which can be connected to any suitable load. Exhaust gases from turbine **25** are passed via conduit **26** to heat exchanger **24** and exhausted therefrom via conduit **27.**

In FIG. **3** there is illustrated a combustor in accordance with the invention, denoted generally by the reference numeral **40,** which comprises an elongated flame tube **42.** Said flame tube **42** 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 or dome member, designated generally by the reference numeral **44,** is provided for closing the upstream end of said flame tube, except for the openings in said dome member. An outer housing or casing **46** is disposed concentrically around said flame tube **42** and spaced apart therefrom to form a first annular chamber **48** around said flame tube and said dome or closure member **44.** Said annular chamber **48** is closed at its downstream end by any suitable means such as that illustrated. Suitable flange members, as illustrated, are provided at the downstream end of said flame tube **42** and outer housing **46** 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 **50** and **52** are provided at the upstream end of said flame tube **42** and said outer housing **46** for mounting same and connecting same to a suitable conduit means which leads from a compressor or other source of air. As illustrated in the drawing, said upstream flange members comprise a portion of said outer housing or casing **46** which encloses dome member **44** and forms the upstream end portion of said first annular chamber **48.** It will be understood that outer housing or casing **46** can be extended, if desired, to enclose dome **44** and said upstream flanges then relocated on the upstream end thereof. While not shown in the drawing, it will be understood that suitable support members are employed for supporting said flame tube 42 and said closure member 44 in the outer housing 46 and said flange members. Said supporting members have been omitted so as to simplify the drawing.

An air inlet means is provided for introducing a swirling mass or stream of air into the upstream end portion of flame tube 42. As illustrated in FIGS. 3 and 6, said air inlet means comprises a generally cylindrical swirl chamber 54 formed in said dome member 44. The downstream end of swirl chamber 54 is in open communication with the upstream end of flame tube 42. A plurality of air conduits 56 extend from said first annular chamber 48, or other suitable source of air, into swirl chamber 54 tangentially with respect to the inner wall thereof.

A fuel inlet means is provided for introducing a stream of fuel into the upstream end portion of flame tube 42. As illustrated in FIG. 3, said fuel inlet means comprises a hollow conduit 58 for introducing a stream of fuel into the upstream end of swirl chamber 54 and axially with respect to said swirling stream of air. Any other suitable fuel inlet means can be employed.

A flared expansion passageway 60 is formed in the downstream end portion of dome or closure member 44. Said flared passageway flares outwardly from the downstream end of swirl chamber 54 to a point on the inner wall of flame tube 42.

An imperforate sleeve 62 surrounds an upstream portion of said flame tube 42. The outer wall of said sleeve can be insulated if desired and thus increase its effectiveness as a heat shield. Said sleeve 62 is spaced apart from flame tube 42 so as to longitudinally enclose an upstream portion 48' of said first annular chamber 48 and define a second annular chamber 64 between said sleeve 62 and outer casing 46. An annular wall member 66, secured to the inner periphery of casing 46, is provided for closing the downstream end of said second annular chamber 64. An annular baffle member 68, secured to the outer wall of flame tube 42 and the inner wall of sleeve 62, is provided for closing the upstream end of said enclosed portion 48' of first annular space 48. At least one opening 70 is provided in the wall of flame tube 42 at a first station located intermediate the ends of said flame tube. In most instances, it will be preferred to provide a plurality of openings 70, as illustrated. A generally tubular conduit means 72 extends from said second annular chamber 64 into communication with said opening 70 for admitting a second stream of air from said second annular chamber 64 into the interior of flame tube 42. When a plurality of openings 70 are provided, a plurality of said tubular conduits 72 are also provided, with each individual conduit 72 being individually connected to an individual opening 70. The above-described structure thus provides an imperforate conduit means comprising second annular chamber 64 and tubular conduit(s) 72 for admitting a second stream of air into the interior of flame tube 42.

At least one other opening 74 is provided in the wall of flame tube 42 at a second station located downstream and spaced apart from said first station for admitting a third stream of air from first annular chamber 48 into the interior of flame tube 42. In most instances, it will be preferred to provide a plurality of openings 74 spaced around the periphery of said flame tube, similarly as illustrated. A second conduit means 15 extends through said outer casing 46, said second annular chamber 64, said sleeve 62, and into communication with said enclosed portion 48' of first annular chamber 48 for admitting a stream of air thereto. If desired, said conduit 15 can communicate with the nonenclosed portion of annular chamber 48.

Preferably, the outer wall surface of flame tube 42 is provided with an extended surface in the form of fins or tabs mounted thereon in the region surrounded by sleeve 62, and which extend into the portion 48' of said first annular chamber which is enclosed by said sleeve. As illustrated in FIGS. 3, 4, and 5, said fins or tabs 76 and 78 can be arranged in rows which extend around the periphery of the flame tube 42, and which are spaced apart longitudinally on said flame tube. The fins or tabs 76, in each row thereof, can be spaced apart circumferentially to provide passageways 77 therebetween. See FIG. 4. Similarly, passageways 79 can be provided between the circumferentially spaced apart fins or tabs 42. See FIG. 5. FIG. 8 illustrates another type of fin which can be employed. In FIG. 8 the fins 80 extend longitudinally of flame tube 42. Said fins 76, 78, and 80 can extend into enclosed portion 48' any desired distance.

FIG. 7 illustrates one type of structure which can be employed to provide tubular conduits 72. A plurality of boss members 82, spaced apart circumferentially in a row around the periphery of flame tube 42, is provided downstream from the last row of fins 78. Said boss members 82 have the general shape of fins 76 and 78 and passageways 83 are provided therebetween, similarly as for passageways 77 and 79 in the rows of fins 76 and 78. Said imperforate sleeve 62 extends over boss members 82, similarly as for fins 76 and 78, and said conduits 72 can be formed by cutting through said sleeve 62 and said boss members 80 into communication with openings 70 in flame tube 42. Said passageways 77, 79 and 83 thus provide communication through enclosed portion 48', around tubular conduits 72, and into the downstream portion of first annular chamber 48.

Referring now to FIG. 9, there is illustrated the upstream portion of another combustor in accordance with the invention. The downstream portion of the combustor of FIG. 9 is like the combustor of FIG. 3. A closure member or dome, designated generally by the reference numeral 85, is mounted in the upstream end of flame tube 42 so as to close the upstream end of said flame tube except for the openings provided in said closure member. Said closure member can be fabricated integrally, i.e., as one element. However, in most instances it will be preferred to fabricate said closure member in a plurality of pieces, e.g., an upstream element 86, a swirl plate 87 (see FIG. 11), and a downstream element or radiation shield 88. An air inlet means is provided for introducing a swirling mass of air into swirl chamber 89 which is formed between swirl plate 87 and radiation shield 88, and then into the upstream end of flame tube 42. As illustrated in FIGS. 9, 10, and 11, said air inlet means comprises a plurality of air conduits 90 and 90' extending through said upstream member 86 and said swirl plate 87, respectively. A plurality of angularly disposed baffles 91, one for each of said air conduits 90, are formed on the downstream side of said swirl plate adjacent the outlets of said air conduits.

A fuel inlet means is provided for introducing a stream of fuel into the upstream end of flame tube 42. As illustrated in FIG. 9, said fuel inlet means comprises a fuel conduit 92 leading from a source of fuel, communicating with a passageway 93 formed in upstream element 86, which in turn communicates with chamber

94, also formed in element 86. A spray nozzle 95 is mounted in a suitable opening in the downstream side of said element 86 and is in communication with said chamber 94. Any other suitable type of spray nozzle and fuel inlet means can be employed, including other air assist atomization nozzles. For example, it is within the scope of the invention to employ other nozzle types for atomizing normally liquid fuels such as nozzles wherein a stream of air is passed through the nozzle along with the fuel.

FIG. 12 is a diagrammatic illustration of another type of combustor which can be employed in the practice of the invention. This combustor is similar to the combustor illustrated in FIG. 3. In the combustor of FIG. 12 the tubular conduits 72' extend transversely through annular chamber 48' and through outer casing 46'. Said tubular conduits 72' can extend to the front or upstream end of the combustor, as illustrated, and be connected to the same source of air as is supplying chamber 48; or said conduits 72' can be connected to another source of air. As here illustrated, said closure member 44' is like closure member 44 in FIG. 3. However, it is within the scope of the invention to employ any other suitable type of closure member, such as closure member 85 in FIG. 10.

In a preferred method of operating the combustor of FIG. 3, a stream of air from a compressor or other source (not shown) is divided into a first stream of air and a second stream of air, said first stream of air is passed, via a conduit connected to flange 52, into the upstream end of annular space 48. Said first stream of air is further divided into a stream comprising primary air and a stream comprising secondary air. Said primary air is passed from annular space 48, through tangential conduits 56, and into swirl chamber 54. Said tangential conduits impart a helical or swirling motion to the air entering said swirl chamber and exiting therefrom. This swirling motion creates a strong vortex action resulting in a reverse circulation of hot gases within flame tube 42.

A stream of fuel, preferably prevaporized, is admitted, via conduit 58, axially of said swirling stream of air. Controlled mixing of said fuel and said air occurs at the interface therebetween. The fuel and air exit from swirl chamber 54 via expansion passageway 60 wherein they are expanded in a uniform and graduated manner, during at least a portion of the mixing thereof, from the volume in the region of the initial contact therebetween to the volume of the primary combustion region, i.e., the upstream portion of flame tube 42.

Said secondary air is passed from the upstream end of annular chamber 48 via second annular chamber 64, tubular conduits 72, and openings 70 into a second region of the combustor which is located downstream from said primary combustion region.

The above-mentioned second stream of air, after passing through a heat exchanger such as heat exchanger 24 in FIG. 1, enters the combustor via conduit 15 and is passed from the upstream end of the enclosed portion 48' of annular chamber 48 through the enclosed portion 48', around tubular conduits 72, into the downstream portion of annular chamber 48, and then via openings 74 into a third region of the combustor which is located downstream from said second region. Said second stream of air comprises and can be referred to as quench or dilution air. Conduit 15 can communicate with enclosed portion 48', or the downstream portion of first annular space or chamber 48, at any desired location. However, the upstream end of enclosed portion 48' is a preferred location because the air flowing over the finned wall portion of flame tube 42 serves to cool said wall portion and remove heat from the interior of said flame tube, and thus cause the primary combustion region to operate at a lower temperature. This aids further in reducing nitrogen oxide emissions.

In one preferred method, the operation of the combustor of FIG. 9 is similar to the above-described operation of the combustor of FIG. 3, and reference is made thereto. The principal difference is in the operation of closure member 85 (FIG. 9) and closure member 44 (FIG. 3). In FIG. 9, primary air is passed through said openings 90 and 90', strikes said baffles 91, and has a swirling motion imparted thereto in chamber 89. A swirling stream of air exits from swirl chamber 89 through the opening in radiation shield 88 which surrounds nozzle 95. A stream of liquid fuel is passed through conduit 92, passageway 93, chamber 94, and exits from nozzle 95 in a generally cone-shaped discharge. Said fuel contacts said stream of air, with said air stream assisting the action of nozzle 95 in atomizing said fuel.

The operation of the combustor illustrated in FIG. 12 is similar to that described above for the combustors of FIGS. 3 and 9, taking into consideration the type of dome or closure member employed on the upstream ends of the flame tubes. The combustor of FIG. 12 is particularly adapted to be employed in those embodiments of the invention wherein the stream of secondary air admitted through openings 70' can have a temperature greater than the temperature of the primary air admitted through dome or closure member 44'. When tubular conduits 72' are connected to the same source of air as is supplying chamber 48, the temperature of the secondary air can be substantially the same as the primary air. Or, the temperature of the secondary air can be increased to be greater than the temperature of the primary air by means of a connection between said conduits 72' and conduit 15', similarly as illustrated in FIGS. 1 and 2. When conduits 72' are connected to a source of air other than that supplying chamber 48, the temperature of the secondary air can be substantially the same as, or greater than, the temperature of the primary air. Any suitable means can be employed for heating said secondary air, e.g., a connection to conduit 15', or a separate heater or heat exchange means for heating the air passing through said conduits 72'.

It is within the scope of the invention to operate the combustors or combustion zones employed in the practice of the invention under any conditions which will give the improved results of the invention. For example, it is within the scope of the invention to operate said combustors or combustion zones at 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 feet 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. Since the invention provides for reducing the temperature of the primary inlet air to the combustor or combustion zone, to values less than those normally employed, so as to reduce nitrogen oxides emissions, it is preferred that the temperature of the inlet primary air be within the range of from ambient to about 700° F., more preferably from ambient to about 500° F. In a preferred embodiment of the invention, the temperature of the secondary air will be about the same as said primary air. However, it is within the scope of the invention for the temperature of the secondary air to be greater, e.g., about 100° to 500° F., preferably about 100° to 300° F., greater than the temperature of said primary air, e.g., when the secondary air is passed over a portion of the flame tube wall or is heated by having a portion of the heated air in conduit **15** mixed therewith via conduit **31,** see FIGS. **1** and **2.** The temperature of the dilution or quench air can be any suitable temperature depending upon materials of construction in the equipment employed downstream from the combustor, e.g., turbine blades, and how much it is desired to cool the combustor effluent. Generally speaking, operating conditions in the combustors employed in the practice 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 relative volumes of the above-described primary, secondary, and quench or dilution air streams will depend upon the other operating conditions. Generally speaking, the combined volume of said primary air and said secondary air will usually be a minor proportion of the total air to the combustor, e.g., less than about 50 volume percent, with said primary air being in the range of up to about 25 volume percent and said secondary air being in the range of up to about 24 volume percent. The volume of said quench or dilution air will usually be a major portion of the total air to the combustor, e.g., more than about 50 volume percent. The relative volumes of said primary, secondary, and quench air streams can be controlled by varying the sizes of the openings, relative to each other, through which said streams of air are admitted to the flame tube. Any other suitable means of controlling said air volumes can be employed, e.g., flow meters on each air stream.

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

The following examples will serve to further illustrate the invention.

EXAMPLE I

A series of runs was made in a combustor typical of prior art combustors. Said combustor basically embodied the principal features of combustors employed in modern aircraft turbine engines. The combustor was a straight-through can-type combustor employing fuel atomization by a single simplex-type nozzle. The combustor liner (flame tube) 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. A commercial Type A jet fuel was employed in these test runs. Runs were made at operating conditions simulating idle conditions and at operating conditions simulating maximum power conditions. 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. 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 of these runs were as follows:

	Test Conditions	
Combustor Operating Variables	Idle	Max. Power
Temp., Inlet Air, °F.	900	1100
Pressure, in. Hg. abs.	50	110
Velocity, Cold Flow, ft./sec.	250	250
Heat Input Rate, Btu/lb. air	200	150
Emissions, lbs./1000 lbs. of fuel		
Nitrogen Oxides	3.4	10.7
Carbon Monoxide	10	0
Hydrocarbons	0.6	0.2

In another series of runs wherein the combustor was operated (using the same fuel) at a pressure of 450 inches of Hg. abs., a gas velocity of 140 feet per second, and a variable heat input rate, it was found that when the air inlet temperature was increased over a range from 400° F. to about 1,150° F., the nitrogen oxides emissions increased substantially uniformly from about 3 to about 23.5 lbs. per 1,000 lbs. of fuel burned.

Based on the above data, it was calculated that a combustor or combustion zone operated in accordance with the method of the invention, at a primary air inlet temperature of about 300° F., would have nitrogen oxides emissions of about 0.6 pound per 1,000 pounds of fuel at idle conditions, and about 0.9 pound per 1,000 pounds of fuel at maximum power conditions.

EXAMPLE II

A series of test runs was carried out employing combustors A and B. Combustor A was like the combustor illustrated in FIG. **3** except that conduit **15** was omitted and a row of fins **76** replaced baffle **68.** Combustor B was like the combustor illustrated in FIG. **9** except that conduit **15** was omitted and a row of fins **76** replaced baffle **68.** Additionally, the fins on the flame tube of combustor B were modified by placing 1/8 inch bars longitudinally through each row of fins **76** and each row of fins **78.** This provided a more linear path through enclosed area **48'.** Design details of said combustors are set forth in Table II below. Said combustors and the design details thereof are here used for illustrative purposes only and the invention is not to be construed as limited thereto. Any suitable combustor having any suitable dimensions can be employed in the practice of the invention. In these runs the heat input (fuel flow) was varied, with the air flow remaining fixed, at different combinations of combustor pressure, reference velocity, and inlet air temperature. Combustor A was run using a prevaporized fuel. Combustor B was run using a liquid atomized fuel. Properties of the fuel used in both combustors are set forth in Table I below.

The method of operation was the same for both combustors. For example, referring to FIG. **3,** a stream of air from a compressor was passed into the upstream end of annular space **48** and there divided. A portion of said air was passed as primary air via inlet conduits **56** into the primary combustion region of the combustor. A second portion of said air was passed as secondary air via annular chamber **64,** tubular conduits **72,** and openings **70** into a secondary combustion region of the combustor. A third portion of said air was passed via enclosed annular chamber **48'** and the downstream portion of annular chamber **48**, and openings **74** into the quench region of the combustor. Like flows were used in the combustor illustrated in FIG. **9**. Using said flows, each of said combustors was operated at the test points or conditions set forth in Table III below. Analyses for emissions content in the combustor exhaust gases were carried out as in Example I. Emissions data for said test runs, mean values from duplicate runs at each test condition, are set forth in Tables IV and V 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
Gravity, degrees API	46.6
Density, lbs/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

TABLE I – Continued

PHYSICAL AND CHEMICAL PROPERTIES OF TEST FUEL

	Philjet A-50
Formula (calculated)	$(C_{11}H_{22})$
Stoichiometric Fuel/Air Ratio, lb./lb.	0.0676

TABLE II

COMBUSTOR DESIGN

Variable	Combustor Number A	Combustor Number B
Closure Member		
Air Inlet Diameter, inches	0.875	0.625
Inlet type	Tangent	Swirl
Hole Diameter, inches	0.188	0.250
Number of Holes	6	6
Total Hole Area, square inches	0.166	0.295
% Total Combustor Hole Area	3.213	5.571
Fuel Nozzle Type	—	Simplex
Spray Angle, degrees	—	45
Fuel Tube Diameter, inches	0.250	—
Flame Tube		
First Station		
Hole Diameter, inches	5/16×1*	5/15×1*
Total Number of Holes	8	8
Total Hole Area, square inches	2.500	2.500
% Total Combustor Hole Area	48.393	47.214
Second Station		
Hole Diameter, inches	5/16×1*	5/16×1*
Total Number of Holes	8	8
Total Hole Area, square inches	2.500	2.500
% Total Combustor Hole Area	48.393	47.214
Combustor Cross-Section Area, square inches	3.355	3.355
Total Combustor Hole Area, square inches	5.166	5.295
% Cross-Sectional Area	153.933	157.777
Combustor Inside Diameter, inches	2.067	2.067
Primary Zone Length, inches	7.375	7.375
Volume, cubic inches	24.748	24.748
Combustor Length, inches	18.437	18.437
Volume, cubic inches	61.867	61.867

*Holes are 5/16 inch diameter at ends; slots are 1 inch long.

TABLE III

TEST CONDITIONS — COMBUSTORS A & B

Test Condition Number	Primary Inlet Air Temperature, °F.	Combustor Pressure, in Hg. abs	Cold Flow Reference Velocity, ft./sec.	Heat Input, Btu/lb. Air	Air Flow, lb./sec.	Fuel Flow, lb./hr.
1	1100	110	250	75	0.545	7.9
2	do.	do.	do.	110	do.	11.6
3	do.	do.	do.	150	do.	15.8
4	do.	do.	do.	185	do.	19.4
5	do.	do.	do.	225	do.	23.6
6	do.	do.	do.	260	do.	27.3
7	do.	do.	do.	300	do.	31.5
8	900	110	250	75	0.625	9.0
9	do.	do.	do.	110	do.	13.3
10	do.	do.	do.	150	do.	18.1
11	do.	do.	do.	185	do.	22.3
12	do.	do.	do.	225	do.	27.1
13	do.	do.	do.	260	do.	31.3
14	do.	do.	do.	300	do.	36.2
15	700	110	250	75	0.733	10.6
16	do.	do.	do.	110	do.	15.5
17	do.	do.	do.	150	do.	21.2
18	do.	do.	do.	185	do.	26.1
19	do.	do.	do.	225	do.	31.8
20	do.	do.	do.	260	do.	36.7
21	do.	do.	do.	300	do.	42.4
22	500	110	250	75	0.885	12.8
23	do.	do.	do.	110	do.	18.8
24	do.	do.	do.	150	do.	25.6
25	do.	do.	do.	185	do.	31.6
26	do.	do.	do.	225	do.	38.4
27	do.	do.	do.	260	do.	44.4
28	do.	do.	do.	300	do.	51.2

TABLE IV

SUMMARY OF EMISSION DATA FROM COMBUSTOR A

Test Condition Number	Primary Zone: Residence Time, msec	Primary Zone: Equivalence Ratio, dia.	Emissions, lb./1000 lb. fuel: NO_x(as NO)	CO	HC (as C)
1	76.6	1.85	19.8	2	0.6
2	do.	2.72	9.4	28	0.3
3	do.	3.71	3.2	26	0.2
4	do.	4.55	3.0	14	0.2
5	do.	5.54	2.4	10	0.2
6	do.	6.40	2.2	9	0.1
7	do.	7.40	2.6	3	0.2
8	76.6	1.84	9.5	51	0.5
9	do.	2.72	4.1	35	1.2
10	do.	3.71	1.6	54	0.8
11	do.	4.56	1.0	46	0.2
12	do.	5.54	0.6	24	0.2
13	do.	6.40	0.9	17	0.1
14	do.	7.40	1.2	2	0.2
15	76.6	1.85	5.7	0	0.5
16	do.	2.70	3.8	94	0.3
17	do.	3.70	1.4	108	0.2
18	do.	4.55	0.9	80	0.2
19	do.	5.54	0.7	30	0.2
20	do.	6.40	0.8	20	0.1
21	do.	7.40	1.4	40	0.7
22	76.6	1.85	4.1	6	1.0
23	do.	2.72	3.5	116	0.9
24	do.	3.70	1.1	134	0.2
25	do.	4.56	0.9	109	0.4
26	do.	5.54	0.8	72	0.4
27	do.	6.40	0.5	86	4.2
28	do.	7.40	0.8	101	8.2

TABLE V

SUMMARY OF EMISSION DATA FROM COMBUSTOR B

Test Condition Number	Primary Zone: Residence Time, msec	Primary Zone: Equivalence Ratio, dia	Emissions, lb./1000 lb. fuel: NO_x(as NO)	CO	HC (as C)
1	44.2	1.07	18.8	0	0.5
2	do.	1.57	7.0	32	0.3
3	do.	2.14	5.7	14	0.4
4	do.	2.63	2.1	6	0.1
5	do.	3.19	1.9	2	0.1
6	do.	3.70	2.2	2	0.2
7	do.	4.26	2.0	1	0.0
8	44.2	1.06	9.4	4	0.5
9	do.	1.57	3.9	77	0.3
10	do.	2.14	1.4	53	0.1
11	do.	2.63	1.4	22	0.3
12	do.	3.20	1.5	7	0.2
13	do.	3.70	1.6	2	0.2
14	do.	4.27	1.8	0	0.1
15	44.2	1.07	6.7	7	0.5
16	do.	1.56	2.8	112	0.3
17	do.	2.13	1.6	122	0.2
18	do.	2.63	1.1	76	0.2
19	do.	3.20	1.0	28	0.2
20	do.	3.69	1.3	10	0.1
21	do.	4.26	1.2	4	0.0
22	44.2	1.07	3.1	10	1.4
23	do.	1.57	1.4	191	0.5
24	do.	2.13	1.1	232	0.3
25	do.	2.63	1.2	153	0.2
26	do.	3.20	0.9	107	0.4
27	do.	3.70	1.0	50	0.6
28	do.	4.26	1.0	26	0.4

The data in the above Tables IV and V show that decreasing the temperature of the inlet air to the primary combustion zone decreases the NO_x emissions. The temperature of the inlet air to the second zone of the combustor (inlet at openings **70**) was not measured but approximated the temperature of the primary air. Thus, the data also show that CO emissions increase with decreasing inlet air temperatures to the secondary combustion zone, and decrease with increasing inlet air temperatures to said secondary combustion zone.

The data from the above runs thus illustrate the advantages of operating a combustor and heat energy utilization system in accordance with the invention. By heat exchanging an exhaust gas stream from the heat energy utilization zone (such as turbine exhaust gases) with one or more other air streams to the combustor such as the quench air (and also heating the secondary air if desired), instead of the primary air, a combustor can be operated with a low primary air inlet temperature, a controlled secondary air inlet temperature which can be the same as or greater than the temperature of the inlet primary air, and a heated quench air stream which can have a greater temperature than either said primary air or said secondary air. The method of the invention thus provides for a low primary inlet air temperature to give low NO_x emissions values, a controlled secondary air inlet temperature to give desired CO emissions values, and a heated quench inlet air to conserve heat energy and increase the overall efficiency of the system.

In general, said data also show that NO_x emissions decrease with increasing equivalence ratio in the primary combustion zone (increasing fuelrich mixture), and tend to plateau at low levels with an increase in heat input. Said equivalence ratios were calculated from the percent Total Combustor Hole Area for the air inlet conduits to the primary combustion zone.

The data set forth in the above Tables IV and V show that combustors can be operated in accordance with the invention to give low NO_x, low CO, and low HC emissions when using either a prevaporized fuel or an atomized liquid fuel. Said data also show that the various operating variables or parameters are interrelated. Thus, a change in one variable or parameter may make it desirable to adjust one or more of the other operating variables or parameters in order to obtain desirable results with respect to all three pollutants NO_x, CO, and HC (hydrocarbons).

In one presently preferred method of the invention, the primary combustion zone is preferably operated fuel-rich with respect to the primary air admitted thereto. Thus, the equivalence ratio in the primary combustion zone is preferably greater than stoichiometric. In this method of operation, the second zone (secondary combustion zone) of the combustor is preferably operated fuel-lean with respect to any unburned fuel and air entering said second zone from said primary zone, and any additional air admitted to said second zone. Thus, the equivalence ratio in said second zone preferably is less than stoichiometric. This method of operation is preferred when it is desired to obtain both low NO_x and low CO emissions from a combustor. In general, it is preferred that the transition from the fuel-rich condition in the primary combustion zone to the fuel-lean condition in the secondary zone be sharp or rapid, e.g., be effected as quickly as possible. While it is presently preferred that the primary combustion zone be operated fuel-rich as described, it is within the scope of the invention to operate the primary combustion zone fuel-lean. Thus, it is within the scope of the invention to operate the primary combustion zone with any equivalence ratio which will give the improved results of the invention.

For example, in the practice of the invention as carried out in low compression ratio combustors, e.g., compression ratios up to about 5, the equivalence ratio in the primary combustion zone can have any value such that the NO_x emissions value in the exhaust gases from the combustor is not greater than about 5 pounds, preferably not greater than about 3.5 pounds, per 1,000 pounds of fuel burned in said combustor. Preferably, said equivalence ratio will be at least 1.5, more preferably at least 3.5, depending upon the other operating variables or parameters, e.g., temperature of the inlet air to the primary combustion zone.

It will be understood that said NO_x emission values referred to in the preceding paragraph can be greater than the values there given when operating high performance combustors. For example, combustors such as the intermediate compression ratio combustors having a compression ratio of about 5 to 15 atmospheres and the high compression ratio combustors having a compression ratio of about 15 to about 40 atmospheres used in jet aircraft and other high performance engines. The NO_x emissions from such high performance or high compression ratio combustors will naturally be higher than the NO_x emissions from low compression ratio combustors. Thus, greatly improved results in reducing NO_x emissions from a high performance combustor can be obtained without necessarily reducing said NO_x emissions to the same levels as would be obtained from a low performance combustor.

As used herein and in the claims, unless otherwise specified, the term "equivalence ratio" for a particular zone is defined as the ratio of the fuel flow (fuel available) to the fuel required for stoichiometric combustion with the air available. Stated another way, said equivalence ratio is the ratio of the actual fuel-air mixture to the stoichiometric fuel-air mixture. For example, an equivalence ratio of 2 means the fuel-air mixture in the zone is fuel-rich and contains twice as much fuel as a stoichiometric mixture.

The data in the above examples show that the temperature of the inlet air to the primary combustion zone can be an important operating variable or parameter in the practice of the invention. As stated above, the invention is not limited to any particular range or value for said inlet air temperature. It is within the scope of the invention to use any primary air inlet temperature which will give the improved results of the invention, for example, from ambient or atmospheric temperatures or lower to about 1,500° F. or higher. However, considering presently available practical materials of construction, about 1,200° F. to about 1,500° F. is a practical upper limit for said primary air inlet temperature in most instances. Considering other practical aspects such as not having to cool the compressor discharge stream, about 200° to 400° F. is a practical lower limit for said primary air inlet temperature in many instances. However, it is emphasized that primary air inlet temperatures lower than 200° F. can be used, e.g., in low compression ratio combustors.

The data in the above examples also show that the temperature of the air admitted to the second zone of the combustor (secondary combustion air) can be an important operating variable or parameter, particularly when the lower primary air inlet temperatures are used, and it is desired to obtain low CO emission values as well as low NO_x emission values. Said data show that both low NO_x emission values and low CO emission values can be obtained when the temperature of the inlet air to both the primary combustion zone and the second zone of the combustor are at least about 900° F. As the temperature of the inlet air to said zones decreases, increasingly improved (lower) values for NO_x emissions are obtained, but it becomes more difficult to obtain desirably low CO emission values. It is preferred that the temperature of the inlet air to the primary combustion zone not be greater than about 700° F. Thus, in some embodiments of the invention, it is preferred that the temperature of the secondary air admitted to the second zone of the combustor be greater than the temperature of the primary air admitted to the primary combustion zone. For example, depending upon the temperature of the inlet air to the primary combustion zone, it is preferred that the temperature of the inlet secondary air be in the range of from about 100° to about 500° F. greater than the temperature of said inlet primary air.

As a guide to those skilled in the art, but not to be construed as necessarily limiting on the invention, the presently preferred operating ranges for other variables or parameters are: heat input, from 30 to 500 Btu per lb. of total air to the combustor; combustor pressure, from 3 to 10 atmospheres; and reference air velocity, from 50 to 250 feet per second.

Reference has been made herein to vehicle emission standards which have been set by the United States Environmental Protective Agency for 1975–1976. These standards or goals have been related to gas turbine engine combustors, by assuming 10.0 miles per gallon fuel economy and 6.352 pounds per gallon JP-4 fuel, as follows:

Emission Level Criteria

Pollutant	EPA Vehicle Standard, grams/mile	Gas Turbine Engine Goal lb./1000 lb. fuel burned
Nitrogen Oxides	0.40 (as NO_2)	0.9
Carbon Monoxide	3.4	11.8
Hydrocarbons	0.41 (as hexane)	1.2 (as carbon)
Particulates	0.03	0.1

The data set forth in the above examples show that the invention can be practiced to give pollutant emission levels meeting tha above standards or goals. However, the invention is not limited to meeting said standards or goals. Many persons skilled in the art consider said standards or goals to be unduly restrictive. It is possible that said standards or goals may be relaxed. Thus, a combustor, and/or a method of operating a combustor, to obtain reduced levels of pollutant emissions approaching said standards or goals has great potential value. While it is not to be considered as limiting on the invention, it is believed that practical maximums for low compression ratio gas turbine engine goals would be in the order of, in lbs. per 1,000 lbs. of fuel burned: NO_x, 5; CO, 25; and hydrocarbons, 2.

Thus, in the practice of the invention, while it is desirable to reduce the nitrogen oxides emissions from the combustors or combustion zones employed therein to values of not more than about 2.5, preferably not more than about 1.8, pounds per 1,000 pounds of fuel burned at idle conditions; and not more than about 5, preferably not more than about 3.5, pounds per 1,000 pounds of fuel burned at maximum power conditions, the invention is not limited to said values.

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.

I claim:

1. In a method wherein a stream of air and a stream of fuel are passed to a combustion zone comprising a primary combustion region, a secondary combustion region located downstream from said primary combustion region, and a quench region located downstream from said secondary combustion region, said fuel and said air are at least partially mixed to form a combustible mixture which is burned to produce hot combustion gases containing heat energy, and said hot combustion gases are passed to a heat energy utilization zone to utilize a portion of said heat energy, the improvement comprising:

dividing said stream of air into a first stream of air and a second stream of air;

further dividing said first stream of air into a stream comprising primary air and another stream comprising secondary air;

introducing a stream of said fuel into said primary combustion region;

introducing said stream comprising primary air into said primary combustion region;

burning said fuel;

introducing said stream comprising secondary air into said secondary combustion region at a temperature within the range of from about 100° to about 500° F. greater than the temperature of said primary air;

passing said second stream of air in heat exchange relationship with an exhaust stream from said heat energy utilization zone to heat said second stream of air and thereby utilize an additional portion of said energy; and

passing at least a portion of said heated second stream of air into said quench region of said combustion zone.

2. A method according to claim **1** wherein the temperature of said primary air is not greater than about 700° F.

3. A method according to claim **2** wherein the equivalence ratio in said primary combustion region is greater than stoichiometric and is adjusted to a value such that the NO_x emissions value in the exhaust gases from said combustion zone is not greater than about 5 pounds per 1,000 pounds of fuel burned in said combustion zone.

4. A method according to claim **3** wherein the CO emissions value in the exhaust gases from said combustion zone is not greater than about 25 pounds per 1,000 pounds of fuel burned in said combustion zone.

5. A method according to claim **4** wherein the equivalence ratio in said primary combustion region is at least about 3.5.

6. A method for forming and burning a combustible mixture of a fuel and air in a combustion zone having a primary combustion region, a secondary combustion region located downstream from said primary combustion region, and a quench region located downstream from said secondary combustion region, to produce hot combustion gases containing heat energy which are passed to a heat energy utilization zone to utilize a portion of said heat energy, which method comprises:

dividing a stream of air into a first stream of air and a second stream of air;

further dividing said first stream of air into a stream comprising primary combustion air and another stream comprising secondary combustion air;

introducing a stream of fuel into said primary combustion region;

introducing said stream comprising primary combustion air into said primary combustion region at a temperature not greater than about 700° F.;

burning said fuel;

introducing said stream comprising secondary combustion air into said secondary region at a temperature within the range of from about **100°** to about 500° F. greater than the temperature of said primary air;

passing said second stream of air in heat exchange relationship with an exhaust stream from said heat energy utilization zone to heat said second stream of air; and

introducing at least a portion of said heated second stream of air into said quench region of said combustion zone.

7. A method for forming and burning a combustible mixture of a fuel and air in a combustion zone having a primary combustion region, a secondary combustion region located downstream from said primary combustion region, and a quench region located downstream from said secondary combustion region, to produce hot combustion gases containing heat energy which are passed to a heat energy utilization zone to utilize a portion of said heat energy, which method comprises:

dividing a stream of air into a first stream of air and a second stream of air;

further dividing said first stream of air into a stream comprising primary combustion air and another stream comprising secondary combustion air;

introducing a stream of fuel into said primary combustion region;

introducing said stream comprising primary combustion air into said primary combustion region at a temperature not greater than about 700° F. and in an amount relative to said fuel sufficient to provide a fuel-rich mixture having an equivalence ratio in said primary combustion region greater than stoichiometric;

burning said fuel;

introducing said stream comprising secondary combustion air into said secondary region, in an amount sufficient to provide a fuel-lean mixture in said secondary region with respect to any unburned fuel entering said secondary region from said primary region, and at a temperature within the range of from about 100° to about 500° F. greater than the temperature of said introduced primary air;

passing said second stream of air in heat exchange relationship with an exhaust stream from said heat energy utilization zone to heat said second stream of air; and

introducing at least a portion of said heated second stream of air into said quench region of said combustion zone at a temperature greater than the temperature of said secondary air.

8. A method according to claim 7 wherein said stream of air comprising primary combustion air is not more than about 25 percent of the total air introduced into said combustion zone.

9. A method according to claim 8 wherein said stream of air comprising primary combustion air is not more than about 5.6 percent of the total air introduced into said combustion zone.

10. A method according to claim 7 wherein said equivalence ratio is adjusted to a value such that the NO_x emissions value in the exhaust gases from said combustion zone is not greater than about 5 pounds per 1,000 pounds of fuel burned in said combustion zone.

11. A method according to claim 10 wherein said equivalence ratio is at least about 1.5.

12. A method according to claim 10 wherein said equivalence ratio is at least about 3.5.

13. A method according to claim 7 wherein the equivalence ratio in said primary combustion region is greater than stoichiometric and is adjusted to a value such that the NO_x emissions value in the exhaust gases from said combustion zone is not greater than about 5 pounds per 1,000 pounds of fuel burned in said combustion zone.

14. A method according to claim 13 wherein the CO emissions value in the exhaust gases from said combustion zone is not greater than about 25 pounds per 1,000 pounds of fuel burned in said combustion zone.

15. A method according to claim 14 wherein said equivalence ratio is at least about 1.5.

16. A method according to claim 14 wherein said equivalence ratio is at least about 3.5.

17. A method for forming and burning a combustible mixture of a fuel and air in a combustion zone having a primary combustion region, a secondary combustion region located downstream from said primary combustion region, and a quench region located downstream from said secondary combustion region, to produce hot combustion gases containing heat energy which are passed to a heat energy utilization zone to utilize a portion of said heat energy, which method comprises:

dividing a stream of air into a first stream of air and a second stream of air;

further dividing said first stream of air into a stream comprising primary combustion air and another stream comprising secondary combustion air;

introducing a stream of fuel into said primary combustion region;

introducing said stream comprising primary combustion air into said primary combustion region;

burning said fuel;

introducing said stream comprising secondary combustion air into said secondary region at a temperature at least 100° F. greater than the temperature of said primary combustion air;

passing said second stream of air in heat exchange relationship with an exhaust stream from said heat energy utilization zone to heat said second stream of air; and

introducing at least a portion of said heated second stream of air into said quench region of said combustion zone.

18. A method according to claim 17 wherein said heated second stream of air is passed in heat exchange with an outer wall of said primary combustion region so as to remove heat from the interior of said primary combustion region and further heat said air, and is then introduced into said quench region.

19. A method according to claim 17 wherein:

said heated second stream of air is passed in a first annular stream surrounding an outer wall of said primary combustion region and a portion of said secondary combustion region, and is then introduced into said quench region; and

said secondary air is passed in a second annular stream surrounding but separated from said first annular stream, and is then introduced into said secondary combustion region.

20. A method according to claim 17 wherein the temperature of said first stream of air is not greater than about 700° F.

21. A method according to claim 17 wherein a portion of said heated second stream of air is mixed with said secondary air so as to increase the temperature of said secondary air.

22. A method for forming and burning a combustible mixture of a fuel and air in a combustion zone having a primary combustion region, a secondary combustion region located downstream from said primary combustion region, and a quench region located downstream from said secondary combustion region, to produce hot combustion gases containing heat energy which are passed to a heat energy utilization zone to utilize a portion of said heat energy, which method comprises:

dividing a stream of air into a first stream of air and a second stream of air;

further dividing said first stream of air into a stream comprising primary combustion air and another stream comprising secondary combustion air;

introducing a stream of fuel into said primary combustion region;

introducing said stream comprising primary combustion air into said primary combustion region in an amount relative to said fuel sufficient to provide a fuel-rich mixture having an equivalence ratio in said primary combustion region greater than stoichiometric;

burning said fuel;

introducing said stream comprising secondary combustion air into said secondary region, in an amount sufficient to provide a fuel-lean mixture in said secondary region with respect to any unburned fuel entering said secondary region from said primary region, and at a temperature at least 100° F. greater than the temperature of said introduced primary air;

passing said second stream of air in heat exchange relationship with an exhaust stream from said heat energy utilization zone to heat said second stream of air; and

introducing at least a portion of said heated second stream of air into said quench region of said combustion zone at a temperature greater than the temperature of said secondary air.

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