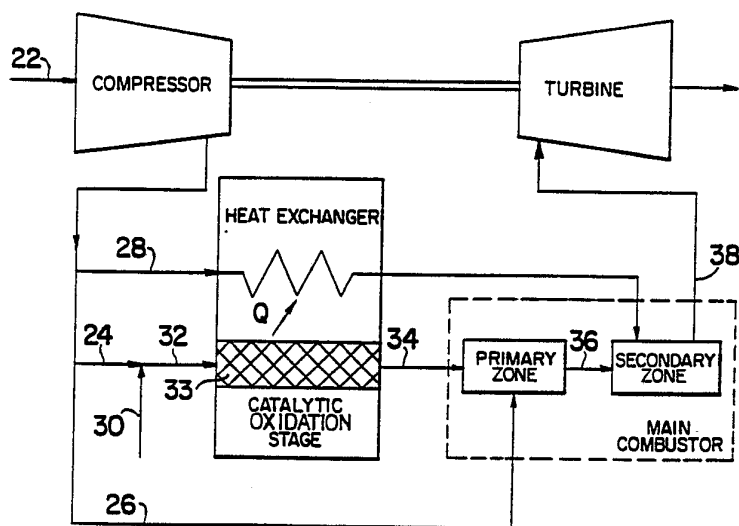




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(54) Title: METHOD AND SYSTEM FOR COMBUSTING HYDROCARBON FUELS WITH LOW POLLUTANT EMISSIONS

**(57) Abstract**

A method of combusting a hydrocarbon fuel (30) includes mixing the fuel (30) with a first air stream (24) to form a fuel/air mixture (32) having an equivalence ratio of greater than 1 and partially oxidizing the fuel by contacting it with an oxidation catalyst (33) to generate a heat of reaction and a partial oxidation product stream (34). The partial oxidation product stream (34) is mixed with a second air stream (26) and completely combusted in a main combustor at a condition at which appreciable quantities of thermal NO_x are not formed to generate an effluent gas stream (38), thereby generating an effluent gas stream (38) containing decreased amounts of thermal and prompt NO_x. A system for combusting a hydrocarbon fuel includes, in combination, means for mixing the fuel with a first air stream, a catalytic oxidation stage containing an oxidation catalyst, means for mixing the partial oxidation product stream with a second air stream, and a main combustor capable of completely combusting the partial oxidation product stream.

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Description
Method and System for Combusting Hydrocarbon
Fuels With Low Pollutant Emissions

Technical Field

5 The present invention relates to a method and system for combusting hydrocarbon fuels with low pollutant emissions, particularly low NO_x emissions.

Background Art

10 It has long been known that exhaust gases produced by combusting hydrocarbon fuels can contribute to atmospheric pollution. Exhaust gases typically contain pollutants such as nitric oxide (NO) and nitrogen dioxide (NO₂), which are frequently grouped together as NO_x, unburned hydrocarbons (UHC), carbon monoxide (CO), and
15 particulates, primarily carbon soot. Nitrogen oxides are of particular concern because of their role in forming ground level smog and acid rain and in depleting stratospheric ozone. NO_x may be formed by several mechanisms. The high temperature reaction of atmospheric
20 oxygen with atmospheric nitrogen, particularly at adiabatic flame temperatures above about 2800°F, forms NO_x through the thermal or the Zeldovich mechanism ("thermal NO_x"). The reaction of atmospheric nitrogen with hydrocarbon fuel fragments (CH_i), particularly under fuel-
25 rich conditions, forms NO_x through the prompt mechanism ("prompt NO_x"). The reaction of nitrogen released from a nitrogen-containing fuel with atmospheric oxygen, particularly under fuel-lean conditions, forms NO_x through the fuel-bound mechanism ("fuel-bound NO_x"). In typical
30 combustors, atmospheric oxygen and nitrogen are readily available in the combustion air which is mixed with the fuel.

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While acknowledging a need to control atmospheric pollution, the more advanced combustion control schemes developed during the past decade were designed to maximize combustion efficiency to maintain economic operation with only a secondary regard for pollutant emissions. For example, the production of CO and UHC was considered undesirable, more because it indicated poor combustion efficiency than because CO and UHC are pollutants. To maximize combustion efficiency and flame stability, fuel is often burned in a diffusion flame at fuel/air ratios as near as possible to stoichiometric, that is, at equivalence ratios of slightly less than 1.0. The equivalence ratio is the ratio of the actual fuel/air ratio to the stoichiometric fuel/air ratio. An equivalence ratio of greater than 1.0 indicates fuel-rich conditions, while an equivalence ratio of less than 1.0 indicates fuel-lean conditions. Burning a fuel at an equivalence ratio slightly less than 1.0 produces nearly complete combustion, minimizing CO and UHC production, and a hot flame, maximizing useable energy. The temperatures produced during such an operation are high enough to produce appreciable quantities of thermal NO_x . Therefore, the goal of achieving good thermal efficiency, which arises from economic concerns, is seemingly at odds with the goal of minimizing NO_x emissions, which arises from environmental concerns and is required by increasingly stringent environmental regulations.

Several fairly simple methods are available to decrease NO_x emissions, although none are entirely satisfactory. For example, the formation of fuel-bound NO_x can be minimized or avoided entirely by burning a low nitrogen or nitrogen-free fuel. However, burning a low nitrogen fuel does nothing to reduce the formation of thermal or prompt NO_x . The formation of thermal NO_x can be reduced by operating under uniformly fuel-lean

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conditions, such as by using a lean diffusion flame or a lean premixed/prevaporized (LPP) system. The excess air used to achieve fuel-lean combustion acts as a diluent to lower flame temperatures, thereby reducing the amount of thermal NO_x formed. The formation of prompt NO_x can also be reduced by operating under fuel-lean conditions because the excess air decreases the concentration of CH_i available to react with atmospheric nitrogen. However, the extent to which thermal and prompt NO_x formation can be reduced by fuel-lean combustion may be limited by flame instability which occurs at very lean conditions.

Accordingly, what is needed in the art is a method and system for efficiently combusting hydrocarbon fuels while minimizing pollutant emissions, particularly NO_x emissions.

Disclosure of the Invention

The present invention is directed to a method and system for efficiently combusting hydrocarbon fuels while minimizing pollutant emissions, particularly NO_x emissions.

One aspect of the invention includes a method of combusting a hydrocarbon fuel. The fuel is mixed with a first air stream to form a fuel/air mixture having an equivalence ratio greater than 1 and partially oxidized by contacting the fuel/air mixture with an oxidation catalyst in a catalytic oxidation stage, thereby generating a heat of reaction and a partial oxidation product stream comprising hydrogen and carbon oxides. The partial oxidation product stream is mixed with a second air stream and completely combusted in a main combustor at a condition at which appreciable quantities of thermal NO_x are not formed, thereby generating an effluent gas stream containing decreased amounts of thermal and prompt NO_x .

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Another aspect of the invention includes a system for combusting a hydrocarbon fuel which includes, in combination, means for mixing the fuel with a first air stream to form a fuel/air mixture having an equivalence ratio greater than 1, a catalytic oxidation stage containing an oxidation catalyst capable of partially oxidizing the fuel to generate a heat of reaction and a partial oxidation product stream comprising hydrogen and carbon oxides, means for mixing the partial oxidation product stream with a second air stream, and a main combustor capable of completely combusting the partial oxidation product stream to generate an effluent gas stream.

The foregoing and other features and advantages of the present invention will become more apparent from the following description and accompanying drawings.

Brief Description of the Drawings

Figure 1 is a schematic representation of a basic combustion system of the present invention.

Figure 2 is a schematic representation of a combustion system of the present invention used in conjunction with a gas turbine engine.

Figure 3 depicts adiabatic flame temperature and NO_x emissions from the combustion system depicted in Fig. 2 and a prior art combustion system as a function of the equivalence ratio in the main combustor primary zone.

Best Mode for Carrying Out the Invention

The present invention uses a combination of three approaches, partial oxidation by catalytic means, thermal management, and flame stability enhancement to control NO_x and other pollutant emissions while permitting thermally efficient combustion of hydrocarbon fuels in a wide variety of combustion devices including residential

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heating units, industrial process heaters, industrial gas turbines, aircraft gas turbines, and advanced aircraft engines such as those contemplated for the high speed civil transport and national aerospace plane projects.

5 These aspects of the present invention may be better understood by referring to Fig. 1, which is a schematic of a basic embodiment of the present invention.

As shown in Fig. 1, an air stream 2, which may be any oxygen containing stream and may be at any suitable
10 temperature and pressure, may be split into two smaller streams, a first air stream 4 and a second air stream 6. The first air stream 4 is mixed with a fuel stream 8, which may be at any suitable temperature and pressure, to form a fuel/air mixture 10 which has an equivalence ratio
15 greater than one. The equivalence ratio may be greater than about 2 and, preferably, will be between about 2.5 and about 8. Most preferably, the equivalence ratio will be between about 3 and about 5. The fuel may comprise C_1 to C_{20} hydrocarbons, C_1 to C_{20} hydrocarbon oxygenates, and
20 blends thereof. Suitable gaseous fuels include natural gas and propane. Suitable liquid fuels include kerosine, No. 1 heating oil, No. 2 heating oil, and conventional aviation turbine fuels such as Jet A, Jet B, JP-4, JP-5, JP-7, and JP-8. If the fuel is a liquid, it should be
25 vaporized or atomized before mixing with the air or while being mixed with the air. Any conventional means known in the art may be used to vaporize or atomize the fuel.

The fuel/air mixture 10 flows into a catalytic oxidation stage where it is contacted with an oxidation
30 catalyst 11 and partially oxidized to generate a heat of reaction and a partial oxidation product stream 12 comprising H_2 , carbon oxides, primarily CO, and unreacted hydrocarbon fuel. Catalytic oxidation in this context means a flameless, rapid oxidation or oxidative pyrolysis
35 reaction carried out at a temperature below that required

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to support thermal combustion, that is, conventional combustion with a flame, and below which thermal NO_x forms in appreciable amounts. Partial oxidation means that there is insufficient oxygen available to completely

5 convert the fuel to CO_2 and H_2O and to fully liberate the chemical energy stored in the fuel. Partially oxidizing the fuel to H_2 , CO , and other carbon oxides by catalytic means reduces the amount of hydrocarbon fuel available to form CH_i fragments in a downstream thermal combustor flame

10 front and therefore, reduces the amount of prompt NO_x formed in downstream combustion. The amount of H_2 , CO , and unreacted hydrocarbon fuel actually formed depends on the temperature in the catalytic oxidation stage, which may range from about 300°F to about 1800°F . At higher

15 temperatures, relatively more fuel is converted to H_2 and CO than at lower temperatures due to changes in the equilibrium product composition. The oxidation catalyst may be any catalyst capable of partially oxidizing the fuel. Suitable catalysts include platinum family metals

20 such as platinum, rhodium, iridium, ruthenium, palladium, and mixtures thereof; chromium oxides; cobalt oxides; and alumina. Preferably, the catalyst will be capable of initiating the partial oxidation reaction at the conditions prevailing in the catalytic oxidation stage,

25 that is, without the addition of heat from an external source. In some applications, however, the catalyst may be preheated using a secondary working fluid, resistive heating, or temporary thermal combustion upstream of the catalyst. The catalyst may be supported on alumina or a

30 similar substrate and may be in any conventional form, including granules, extrudates, or a coating on a metal heat exchanger surface, metal foil, metal honeycomb, or ceramic honeycomb. The preferred catalysts include platinum family metals, especially platinum-rhodium

35 deposited on an alumina support. If desired, more than

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one catalyst may be incorporated into a graded catalyst bed. The catalytic oxidation stage may be designed according to conventional catalytic reactor design techniques.

5 At the same time the partial oxidation reaction takes place, a portion of the heat of reaction may be extracted from the catalytic oxidation stage by heat transfer stream 14 to control the temperature and composition of the partial oxidation product stream 12.

10 This operation will be referred to as thermal management. Extracting a small amount of heat or no heat from the catalytic oxidation stage produces a relatively hot partial oxidation product stream having a relatively large amount of H_2 and relatively lower amounts of

15 unreacted hydrocarbon fuel. As a result, relatively little prompt NO_x will be formed in downstream combustion. Extracting a relatively large amount of heat from the catalytic oxidation stage produces a relatively cool partial oxidation product stream having a relatively

20 lower amount of H_2 and a relatively larger amount of unreacted hydrocarbon fuel. Any increase in prompt NO_x resulting from the larger amount of unreacted hydrocarbon fuel will be at least partially offset by a reduction in thermal NO_x formed in a downstream thermal combustor where

25 the cooler partial oxidation product stream produces a lower adiabatic flame temperature. By using thermal management to control the temperature and composition of the partial oxidation product stream, the total amount of NO_x formed in the combustion system can be controlled to

30 suit specific operating conditions. Thermal management may be used to extract up to about 50% of the heat of reaction generated in the catalytic oxidation stage. Preferably, up to about 20% of the heat of reaction will be extracted and, most preferably, about 3% to about 20%

35 of the heat of reaction will be extracted. If desired,

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the heat extraction may take place downstream of the catalytic oxidation stage, in which case only the temperature of the partial oxidation product stream 12 may be controlled. A heat exchanger may be used to
5 extract a portion of the heat of reaction. The heat exchanger may be designed according to conventional heat exchanger design techniques and may be an integral part of the catalytic oxidation stage or may be a separate unit. The heat transfer stream 14 may initially be at
10 any temperature which permits heat to be extracted from the catalytic oxidation stage or partial oxidation product stream, while its temperature after thermal management will depend on the amount of heat extracted. The heat transfer stream 14 may be air, water, or another
15 medium and, after thermal management, can be used in any capacity for which a person skilled in the art would consider such a heated stream to be useful. Effective use of the heat transfer stream 14 permits the thermal efficiency of the present invention to be at least as
20 good as a conventional combustion system.

After catalytic oxidation and thermal management, the cooled partial oxidation product stream 12 is mixed with the second air stream 6 in a main combustor and is completely combusted by a thermal combustion reaction,
25 generating an exhaust gas stream 16. The cooled partial oxidation product stream may be mixed with the second air stream prior to combustion or in a diffusion flame. Preferably, the adiabatic flame temperature in the main combustor will be less than about 2800°F to minimize the
30 formation of thermal NO_x. The adiabatic flame temperature and flame stability characteristics in the main combustor depend on the temperature and composition of the partial oxidation product stream and the equivalence ratio in the combustor. In general, the H₂ in the partial oxidation
35 product stream enhances flame stability because H₂ is

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lighter and more reactive than the original fuel and mixes better with the second air stream. Flame stability is especially enhanced when little or no heat is extracted from the catalytic oxidation stage because the partial oxidation product stream will contain more H_2 and will be hotter, leading to better mixing. A more stable flame permits the main combustor to be operated at a lower equivalence ratio, which produces a lower adiabatic flame temperature and less thermal NO_x . In any case, the main combustor should be operated at an overall equivalence ratio of less than 1.0 to ensure complete combustion. The main combustor may be any combustor suitable for combusting the partial oxidation product stream, including a conventional or advanced combustor, and may have either a single combustion zone or a plurality of combustion zones. Preferably, the main combustor will be a lean premixed prevaporized combustor. The main combustor may be designed according to conventional techniques.

As shown in Fig. 2, combining the present invention with a gas turbine provides some additional benefits. Air stream 22 enters a compressor and is compressed to a suitable temperature and pressure. The air exiting the compressor is controllably divided into three streams, a first air stream 24, a primary air stream 26, and a secondary air stream 28. The first air stream 24 mixes with a fuel stream 30 to form a fuel/air mixture 32 having an equivalence ratio greater than 1.0. The fuel/air mixture 32 enters a catalytic oxidation stage where it is contacted with an oxidation catalyst 33 and partially oxidized to produce a heat of reaction and a partial oxidation product stream 34 comprising H_2 and carbon oxides. A portion of the heat of reaction is removed in a heat exchanger by the secondary air stream 28, heating the secondary air stream 28 and cooling the

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partial oxidation product stream 34. The cooled partial oxidation product stream 34 mixes with the primary air stream 26 and is thermally combusted in a primary zone of a main combustor at a temperature at which appreciable quantities of thermal NO_x are not formed to generate a combustion product stream 36. The fuel/air equivalence ratio in the primary zone may be greater than 1.0, or less than 1.0, but preferably, will be less than 1.0 to minimize both thermal and prompt NO_x formation. The combustion product stream 36 is diluted with the secondary air stream 28 which may be added to the secondary zone through dilution holes in the main combustor to generate an exhaust gas stream 38. The secondary air dilutes and cools the combustion product stream 36 and returns the heat extracted from the catalytic combustion stage to the exhaust gas stream 38. As a result, the temperature of the exhaust gas stream 38, the thermal efficiency of the combustion system, and the amounts of CO and UHC in the exhaust gas are nearly identical to what they would have been if a conventional combustion scheme had been used. Alternately, instead of using all of the secondary air stream 28 as dilution air, a portion of the secondary air stream 28 may be added to the primary zone to provide additional combustion air. After exiting the secondary zone, the exhaust gas stream 38 is expanded across a turbine to produce shaft work to drive the compressor. The exhaust gases may also be used for propulsion or to produce additional shaft work.

A system such as that depicted in Fig. 2 can provide gas turbines with significant additional operating flexibility, particularly when the turbines are operated off peak power. The improved flame stability provided by burning a lighter, more reactive fuel in the main combustor provides wider flammability limits than are available from other fuels, permitting combustion to be

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maintained at lower equivalence ratios. Additionally, the ability to control the division of the air stream into a primary stream and a secondary stream can be used to provide dynamic control of the equivalence ratio in the primary zone so that it is kept constant as power levels are changed.

Example 1

A gas turbine engine incorporating a catalytic oxidation stage and a two zone main combustor as shown in Fig. 2 was modelled on a computer using conventional techniques which are well known in the art. The catalytic oxidation stage was represented by a detailed chemical kinetic model, the main combustor primary zone was represented by a perfectly stirred reactor, and the main combustor secondary zone was represented by a plug flow reactor. Compressed air at 18.9 atmospheres and 847°F was split into three streams: 7.5% of the air to the first air stream, 42.5% of the air to the primary air stream, and 50% of the air to the secondary air stream. The first air stream was mixed with methane, which was at 80°F, to form a fuel/air mixture which had an equivalence ratio of 4.0 and a temperature of 564°F. The fuel/air mixture was partially oxidized in the catalytic oxidation stage to produce a partial oxidation product stream comprising 12 volume percent (vol%) CH_4 , 8 vol% CO , and 19 vol% H_2 . The residence time in the catalytic oxidation stage was 20 milliseconds (msec) and the temperature was maintained at 1340°F by using thermal management to heat the secondary air stream to 1192°F. The partial oxidation product stream, which exited the catalytic stage at 1340°F, was mixed with the primary air stream in the main combustor primary zone and thermally combusted with a residence time of 0.1 msec and an equivalence ratio of 0.6. The combustion product stream, which was at 2750°F and contained 6 parts per million (ppm) NO and

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6,000 ppm CO, was mixed with the secondary air stream in the main combustor secondary zone with a residence time of 6.0 msec and an equivalence ratio of 0.3 to produce an exhaust gas stream. The exhaust gas stream exited the secondary zone at 2049°F and contained 3 ppm NO and 6 ppm CO.

Example 2

The model from Example 1 was used to model a range of operations in the main combustor. Conditions in the catalytic oxidation stage were maintained at 1250°F and an equivalence ratio of 4 for all cases. Methane and natural gas were used as the fuels for this example. The equivalence ratio in the primary zone was varied from 0.6 to 1.5 and the adiabatic flame temperature was permitted to vary accordingly. The equivalence ratio in the secondary zone was fixed at 0.3. A model of a prior art combustion system with an identical main combustor but lacking a catalytic oxidation stage was also prepared. The model of the prior art system was run at the same conditions as the first model, except that methane, instead of a partial oxidation product stream, was fed to the primary zone. Data from both models are presented in Fig. 3. Curves 31 and 32 and the right hand scale show the primary zone adiabatic flame temperatures computed for the various primary zone equivalence ratios. Curves 33 and 34 and the left hand scale show the computed NO_x concentrations in the secondary zone exhaust gas for the various primary zone equivalence ratios. Curves 31 and 33 represent operations with the prior art combustion system. Curves 32 and 34 represent operations with the present invention. Fig. 3 demonstrates that the present invention can reduce NO_x emission levels by a factor of three to five at a given equivalence ratio and can reduce adiabatic flame temperatures by several hundred degrees at a given equivalence ratio.

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The present invention is capable of providing several benefits over the prior art. First, it provides three techniques, partial oxidation by catalytic means, thermal management, and flame stabilization, by which NO_x and other pollutant emissions can be reduced while maintaining good thermal efficiency. The extent to which any of the three techniques is used can be varied to optimize the combustion system operation and design.

Second, because many of the hydrocarbon molecules in the fuel are converted to H₂ and carbon oxides in the catalytic oxidation stage, fewer hydrocarbon molecules are available for soot production in the main combustor. Lower soot production results in fewer particulate emissions and less radiative heat transfer to combustor walls. Third, the decrease in adiabatic flame temperatures in the main combustor due to thermal management, combined with less radiative heating, can prolong the life of combustor materials or permit the use of less expensive materials.

Fourth, the ability to control the amount of air directed to the primary and secondary zones of the main combustor permits dynamic control of the equivalence ratio in the primary zone for off peak operations. Such a control scheme would be particularly beneficial in gas turbines.

Fifth, the present invention has the flexibility to be used with rich-burn-quench-lean-burn, or other advanced combustion techniques to further reduce NO_x emissions.

It should be understood that the invention is not limited to the particular embodiments shown and described herein, but that various changes and modifications may be made without departing from the spirit or scope of the claimed invention.

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Claims

1. A method of combusting a hydrocarbon fuel, comprising:

- 5 (a) mixing the fuel with a first air stream to form a fuel/air mixture having an equivalence ratio greater than 1;
- (b) partially oxidizing the fuel by contacting the fuel/air mixture with an oxidation catalyst in a catalytic oxidation stage, thereby generating a heat of reaction and a partial oxidation product stream comprising hydrogen and carbon oxides;
- 10 (c) mixing the partial oxidation product stream with a second air stream; and
- 15 (d) completely combusting the partial oxidation product stream in a main combustor at a condition at which appreciable quantities of thermal NO_x are not formed, thereby generating an effluent gas stream containing decreased amounts of thermal and prompt NO_x .

2. The method of claim 1, further comprising, extracting a portion of the heat of reaction after step (b), thereby cooling the partial oxidation product stream.

3. The method of claim 2 wherein up to about 50% of the heat of reaction is extracted after step (b).

4. The method of claim 2, further comprising, transferring the heat extracted after step (b) to the effluent gas stream, thereby heating the effluent gas stream.

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5. The method of claim 4, further comprising, expanding the heated effluent gas stream across a turbine, thereby producing power.

6. The method of claim 4 wherein the main combustor comprises a primary zone and a secondary zone and the heat extracted after step (b) is transferred to the effluent gas stream in the secondary zone.

7. The method of claim 2 wherein the heat is extracted from the catalytic oxidation stage, thereby cooling both the catalytic oxidation stage and partial oxidation product stream.

8. The method of claim 1 where in the equivalence ratio in the catalytic oxidation stage is at least about 2.

9. The method of claim 1 wherein the oxidation catalyst is selected from the group consisting of platinum, rhodium, iridium, ruthenium, palladium, and mixtures thereof; chromium oxides; cobalt oxides; and alumina.

10. The method of claim 1 wherein the partial oxidation product stream and second air stream are mixed prior to combustion.

11. The method of claim 1 wherein the partial oxidation product stream and second air stream are mixed in a diffusion flame.

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12. A method of combusting a hydrocarbon fuel in a gas turbine engine, comprising:

- (a) compressing an air stream in a compressor;
- (b) controllably dividing an air stream into a
5 first air stream, a primary air stream, and a secondary air stream;
- (c) mixing the fuel with the first air stream to form a fuel/air mixture having an equivalence ratio greater than 1;
- 10 (d) partially oxidizing the fuel by contacting the fuel/air mixture with an oxidation catalyst in a catalytic oxidation stage, thereby generating a heat of reaction and a partial oxidation product stream comprising hydrogen and carbon
15 oxides;
- (e) transferring a portion of the heat of reaction to the secondary air stream, thereby cooling the partial oxidation product stream;
- (f) mixing the cooled partial oxidation product
20 stream with the primary air stream;
- (g) combusting the cooled partial oxidation product stream in a primary zone of a main combustor at a condition at which appreciable quantities of thermal NO_x are not formed, thereby generating a
25 combustion product stream;
- (h) mixing the combustion product stream with the heated secondary air stream, thereby generating an effluent gas stream; and
- 30 (i) expanding the effluent gas stream across a turbine, thereby producing power.

13. A system for combusting a hydrocarbon fuel, comprising in combination:

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- 5 (a) means for mixing the fuel with a first air stream to form a fuel/air mixture having an equivalence ratio greater than 1;
- 10 (b) a catalytic oxidation stage containing an oxidation catalyst capable of partially oxidizing the fuel to generate a heat of reaction and a partial oxidation product stream comprising hydrogen and carbon oxides;
- (c) means for mixing the partial oxidation product stream with a second air stream; and
- 15 (d) a main combustor capable of completely combusting the partial oxidation product stream to generate an effluent gas stream.

14. The system of claim 13, further comprising, means for extracting a portion of the heat of reaction from the catalytic oxidation stage or partial oxidation product stream, thereby cooling the partial oxidation product stream.

5

15. The system of claim 14, further comprising, means for transferring the extracted heat to the effluent gas stream to heat the effluent gas stream.

16. The system of claim 15, further comprising, means for expanding the heated effluent gas stream across a turbine to produce power.

17. The system of claim 15 wherein the main combustor comprises a primary zone and a secondary zone and means for transferring the extracted heat to the effluent gas stream in the secondary zone.

18. The system of claim 13 wherein the oxidation catalyst is selected from the group consisting of

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platinum, rhodium, iridium, ruthenium, palladium, and
mixtures thereof; chromium oxides; cobalt oxides; and
5 alumina.

19. The system of claim 13 wherein the means for mixing
the partial oxidation product stream with a second air
stream permit the mixing to occur prior to combustion.

20. The system of claim 13 wherein the means for mixing
the partial oxidation product stream with a second air
stream permit the mixing to occur in a diffusion flame.

21. A system for combusting a hydrocarbon fuel,
comprising in combination:

- 5 (a) means for controllably dividing a compressed
air stream into a first air stream, a primary
air stream, and a secondary air stream;
- (b) means for mixing the fuel with the first air
stream to form a fuel/air mixture having an
equivalence ratio greater than 1;
- 10 (c) a catalytic oxidation stage containing an
oxidation catalyst capable of partially
oxidizing the fuel to generate a heat of
reaction and a partial oxidation product stream
comprising hydrogen and carbon oxides;
- 15 (d) means for transferring a portion of the heat of
reaction to the secondary air stream, thereby
cooling the partial oxidation product stream;
- (e) means for mixing the cooled partial oxidation
product stream with the primary air stream;
- (f) a primary zone of a main combustor capable of
combusting the cooled partial oxidation product
stream to generate a combustion product stream;
- (g) means for mixing the combustion product stream
with the heated secondary air stream;

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- (h) a secondary zone of the main combustor capable of diluting the combustion product stream to generate an effluent gas stream.

AMENDED CLAIMS

[received by the International Bureau on 19 October 1992 (19.10.92);
original claim 14 deleted; original claims 1-4,7,13,15 and 17 amended;
remaining claims unchanged (6 pages)]

1. A method of combusting a hydrocarbon fuel,
comprising:
 - (a) mixing the fuel with a first air stream to form
a fuel/air mixture having an equivalence ratio
greater than 1;
 - (b) partially oxidizing the fuel by contacting the
fuel/air mixture with an oxidation catalyst in
a catalytic oxidation stage, thereby generating
a heat of reaction and a partial oxidation
product stream comprising hydrogen and carbon
oxides;
 - (c) extracting up to about 50% of the heat of
reaction, thereby cooling the partial oxidation
product stream;
 - (d) mixing the partial oxidation product stream
with a second air stream; and
 - (e) completely combusting the partial oxidation
product stream in a main combustor at a
condition at which appreciable quantities of
thermal NO_x are not formed, thereby generating
an effluent gas stream containing decreased
amounts of thermal and prompt NO_x .
2. The method of claim 1 wherein the heat extracted in
step (c) is controllably extracted from the catalytic
oxidation stage at the same time the fuel is partially
oxidized to control the temperature and composition of
the partial oxidation product stream, wherein the
temperature of the partial oxidation product stream
affects the amount of thermal NO_x formed in the main
combustor, the composition of the partial oxidation
product stream determines the amount of prompt NO_x formed
in the main combustor, and the temperature and
composition of the partial oxidation product stream

affect the stability of a flame in the main combustor, whereby the temperature and composition of the partial oxidation product stream are selected to control
15 simultaneously the amounts of thermal NO_x and prompt NO_x formed in the main combustor and the stability of the flame in the main combustor, thereby controlling the total amount of NO_x in the effluent gas stream.

3. The method of claims 1 or 2 wherein at least about 3% of the heat of reaction is extracted in step (c).

4. The method of claims 1, 2, or 3, further comprising, transferring the heat extracted in step (c) to the effluent gas stream, thereby heating the effluent gas stream.

5. The method of claim 4, further comprising, expanding the heated effluent gas stream across a turbine, thereby producing power.

6. The method of claim 4 wherein the main combustor comprises a primary zone and a secondary zone and the heat extracted in step (c) is transferred to the effluent gas stream in the secondary zone.

7. The method of claim 1 wherein the heat is extracted from the catalytic oxidation stage, thereby cooling both the catalytic oxidation stage and partial oxidation product stream.

8. The method of claim 1 where in the equivalence ratio in the catalytic oxidation stage is at least about 2.

9. The method of claim 1 wherein the oxidation catalyst is selected from the group consisting of platinum, rhodium, iridium, ruthenium, palladium, and mixtures thereof; chromium oxides; cobalt oxides; and
5 alumina.

10. The method of claim 1 wherein the partial oxidation product stream and second air stream are mixed prior to combustion.

11. The method of claim 1 wherein the partial oxidation product stream and second air stream are mixed in a diffusion flame.

13. A system for combusting a hydrocarbon fuel, comprising in combination:

- 5 (a) means for mixing the fuel with a first air stream to form a fuel/air mixture having an equivalence ratio greater than 1;
- (b) a catalytic oxidation stage containing an oxidation catalyst capable of partially oxidizing the fuel to generate a heat of reaction and a partial oxidation product stream comprising hydrogen and carbon oxides;
- 10 (c) means for controllably extracting a portion of the heat of reaction from the catalytic oxidation stage at the same time the fuel is partially oxidized to control the temperature and composition of the partial oxidation product stream, wherein the temperature of the partial oxidation product stream affects the amount of NO_x formed in a main combustor downstream of the catalytic oxidation stage, the composition of the partial oxidation product stream determines the amount of prompt NO_x formed in the main combustor, and the temperature and composition of the partial oxidation product stream affect the stability of a flame in the main combustor;
- 15 (d) means for mixing the partial oxidation product stream with a second air stream; and
- 20 (e) a main combustor capable of completely combusting the partial oxidation product stream to generate an effluent gas stream.
- 25
- 30

15. The system of claim 13, further comprising, means for transferring the extracted heat to the effluent gas stream to heat the effluent gas stream.

16. The system of claim 15, further comprising, means for expanding the heated effluent gas stream across a turbine to produce power.

17. The system of claims 15 or 16 wherein the main combustor comprises a primary zone and a secondary zone and means for transferring the extracted heat to the effluent gas stream in the secondary zone.

18. The system of claim 13 wherein the oxidation catalyst is selected from the group consisting of platinum, rhodium, iridium, ruthenium, palladium, and mixtures thereof; chromium oxides; cobalt oxides; and
5 alumina.

19. The system of claim 13 wherein the means for mixing the partial oxidation product stream with a second air stream permit the mixing to occur prior to combustion.

20. The system of claim 13 wherein the means for mixing the partial oxidation product stream with a second air stream permit the mixing to occur in a diffusion flame.

21. A system for combusting a hydrocarbon fuel, comprising in combination:

- 5 (a) means for controllably dividing a compressed air stream into a first air stream, a primary air stream, and a secondary air stream;
- (b) means for mixing the fuel with the first air stream to form a fuel/air mixture having an equivalence ratio greater than 1;
- 10 (c) a catalytic oxidation stage containing an oxidation catalyst capable of partially oxidizing the fuel to generate a heat of reaction and a partial oxidation product stream comprising hydrogen and carbon oxides;
- 15 (d) means for transferring a portion of the heat of reaction to the secondary air stream,

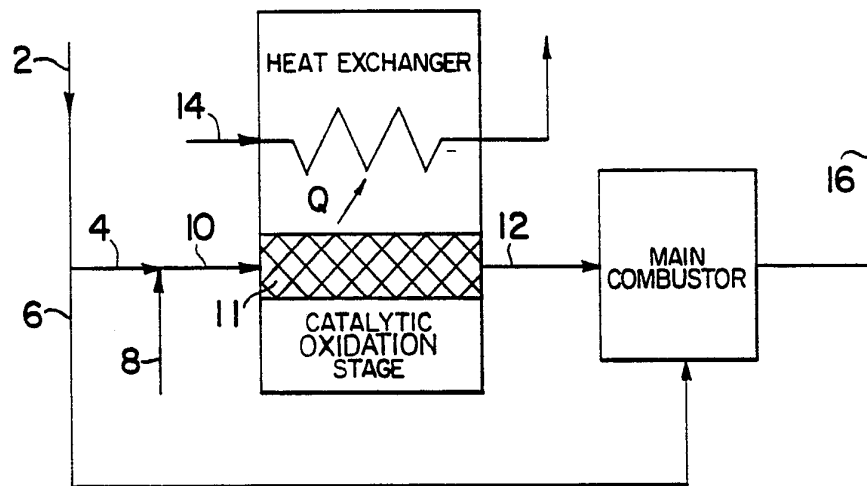
$$1/2$$


FIG. 1

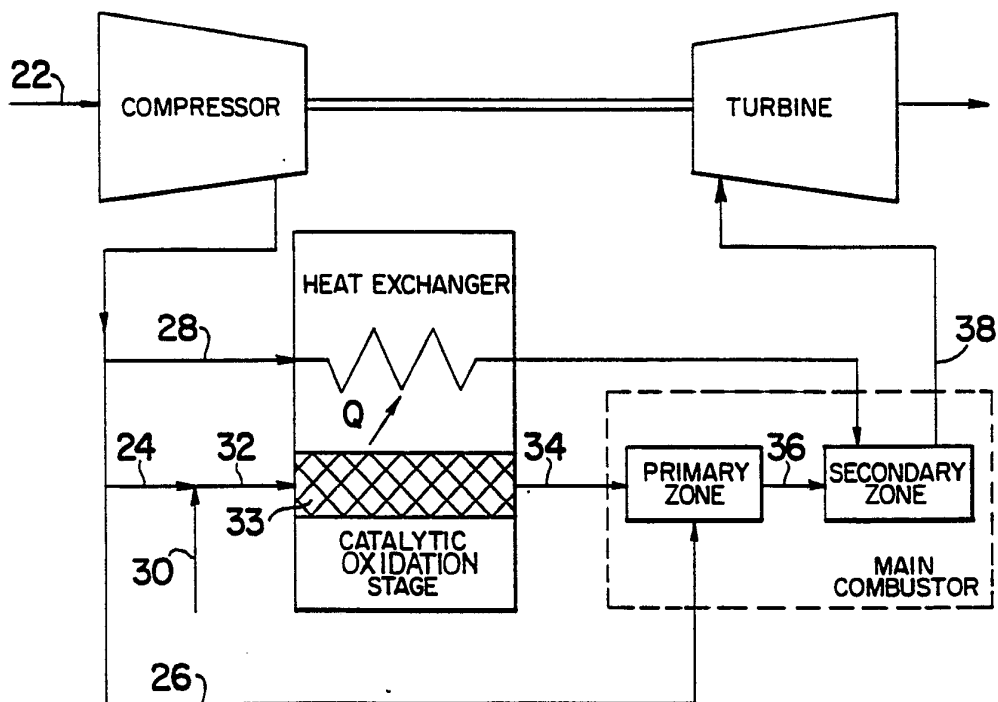


FIG. 2

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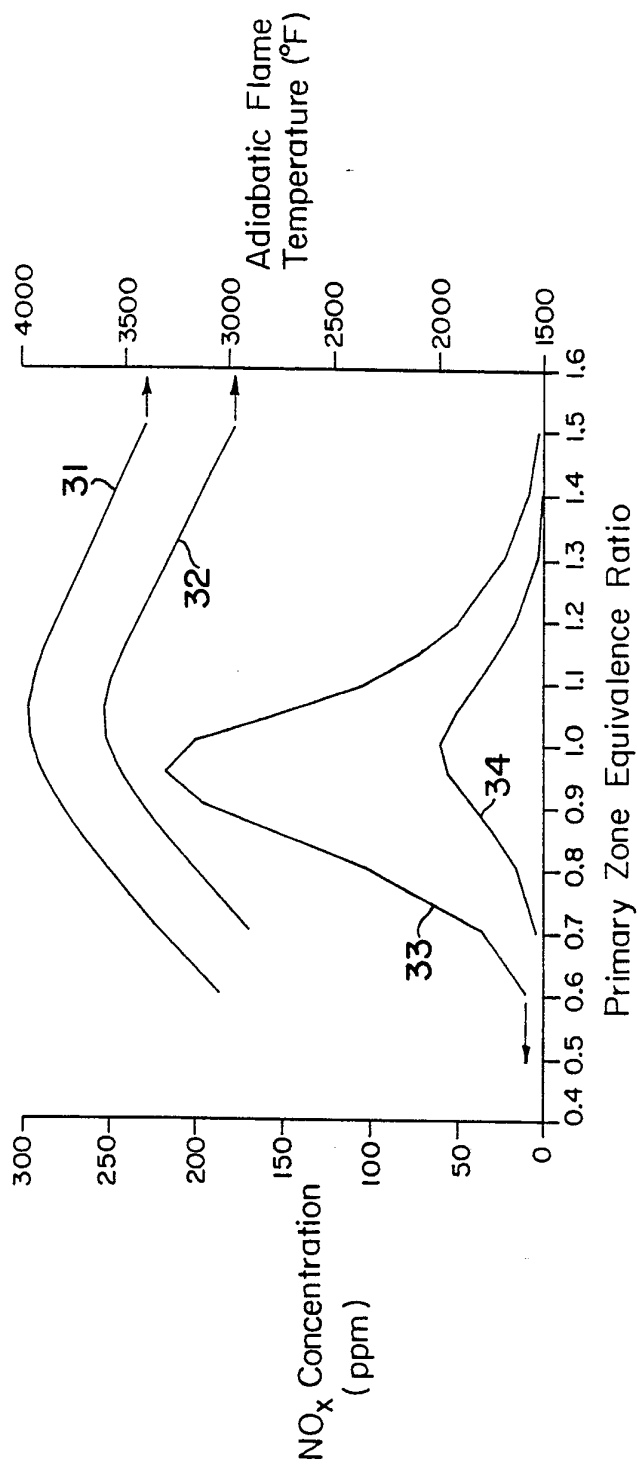


FIG. 3

INTERNATIONAL SEARCH REPORT

International Application No

PCT/US 92/03771

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) ⁶		
According to International Patent Classification (IPC) or to both National Classification and IPC-		
Int.Cl. 5	F23C6/04; F23R3/40;	F23C11/00; F02C3/20
		F02M27/02; F02B51/02
II. FIELDS SEARCHED		
Minimum Documentation Searched ⁷		
Classification System	Classification Symbols	
Int.Cl. 5	F23C ; F02M ;	F23R ; F02B
	F02K ;	F02C
Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched ⁸		
III. DOCUMENTS CONSIDERED TO BE RELEVANT⁹		
Category ¹⁰	Citation of Document, ¹¹ with indication, where appropriate, of the relevant passages ¹²	Relevant to Claim No. ¹³
X	DE,A,2 618 961 (NISSAN) 11 November 1976 see page 41, paragraph 2 - page 43, paragraph 1 see figure 32	1,8,11, 13,20
Y	---	2,9,10, 14,18,19 12,21
A	---	
Y	GB,A,1 460 312 (TOKYO GAS COMPANY) 6 January 1977 see the whole document	2,14
Y	---	9,18
	DE,A,2 103 008 (SIEMENS) 3 August 1972 see page 3, paragraph 4 - page 5, paragraph 1 see figure	

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¹⁰ Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier document but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art. "&" document member of the same patent family		
IV. CERTIFICATION		
Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report	
21 SEPTEMBER 1992	02. 10. 92	
International Searching Authority	Signature of Authorized Officer	
EUROPEAN PATENT OFFICE	LEITNER J.	

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)		
Category °	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No.
Y	US,A,4 459 126 (KRILL) 10 July 1984 see column 2, line 59 - column 3, line 33 see figure 1 ---	10,19
A	US,A,4 179 880 (SCHIRMER) 25 December 1979 see column 3, line 45 - column 5, line 19 see figures 1,2 -----	12,21

**ANNEX TO THE INTERNATIONAL SEARCH REPORT
ON INTERNATIONAL PATENT APPLICATION NO.**

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This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report. The members are as contained in the European Patent Office EDP file on
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information. 21/09/92

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