

TITLE OF THE INVENTION:

5 IMPROVED FUEL STAGING PROCESS FOR LOW
NO_x OPERATIONS

BACKGROUND OF THE INVENTION

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[0001] The present invention relates to fuel staging processes and systems for reducing nitrogen oxide (NO_x) emissions, and in particular to such processes and systems using fuel dilution tips in low NO_x burners.

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[0002] One of the challenges confronting the Chemical Process Industry (CPI) is the combustion of waste fuels for economic reasons and at the same time meeting low NO_x and CO emissions requirements. The waste fuels contain a cocktail of higher C/H ratio gases which combust with very luminous flames due to carbon oxidation and also produce soot particles or carbon depending on the combustion process. Typical refinery fuel composition contains varying amounts of fuels and inert gases (e.g., C₁, C₂, C₃,...C_n, olefins, hydrogen, nitrogen, CO₂, water vapor). If carbon or soot particles are formed on the fuel tips, the soot structure generally grows under favorable pressure and temperature conditions existing near the tip exit. This could result in fuel jet blockage, fuel jet deflection, and overheating of tips and furnace parts, such as process tubes and refractory walls, and the potential shutdown of the burners and furnace operation. The shutdown of a furnace could result in significant financial penalties, including liability arising from downstream process interruption.

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[0003] Dirty refinery fuels consisting of higher carbon and containing gases such as acetylene, ethane, propane, butane and olefins (e.g., ethylene and propylene) generally produce soot particles if fuel tips are subjected to:

- inadequate mixing in the furnace (depending on the number of jets, jet geometry, injection angles and injection velocities not being optimum) (generally classified as a burner design issue);
- lack of combustion air or oxidant availability in the vicinity of fuel jets (generally classified as a burner flow configuration issue);
- inadequate cooling of fuel tips (exposure to furnace radiation on regular basis) (generally classified as a fuel tip configuration and burner design issue);
- interruption of fuel flows (upstream fuel equipment reliability) (generally classified as a process issue);
- lower firing operation (lower fuel flow rates due to process turndown) (generally classified as a process issue); or
- fluctuation of refinery fuel composition in terms of carbon containing species (generally classified as a process requirement issue).

[0004] The burner or tip design significantly affect tip overheating, soot production, tip plugging, and resulting frequent maintenance for the burner equipment. These problems are compounded by changing process conditions, such as low end of process turndown and/or interruption of fuel flows, which affect required cooling needed on the fuel tips. Changing process conditions and fuel composition changes are common in refinery operation.

[0005] Another challenge confronting the CPI is the requirement of low NO_x emissions to meet emission regulations. There are various areas in the United States where NO_x regulations (under the 1990 Clean Air Act) require less than 10 ppm NO_x emissions from process heaters, boilers, gas turbines, and other stationary combustion equipment. The most common or BACT (Best Available Control Technology) solution in the CPI is to use a SCR (Selective Catalytic Reactor) for post cleanup of flue gas for reduction of NO_x contained in the flue stream (by converting NO_x into N₂) using ammonia injection inside a

large catalytic reactor. This process is very capital intensive and requires significant quantities of ammonia, hot air, and electricity for ID fan operation.

[0006] Most refineries would like to avoid SCR installation and instead use low NOx burners to meet their NOx compliance requirements. However, low NOx burners have not consistently produced less than 10 ppm NOx in various process heating applications, such as steam methane reformers (SMR), crude heaters, ethylene crackers, or boilers. For this reason, the use of low NOx burners has not been certified by regulating agencies as the BACT. In other words, SCR currently is the only commercially viable solution for meeting stringent NOx levels in ozone attainment regions where ground level ozone concentration exceeds legal limits.

[0007] Typically, operators in the CPI utilize clean natural gas or an optimum blend of natural gas and dirty refinery fuels to reduce penalties on maintenance issues. However, due to natural gas shortages and the high cost of fuels, it is not always possible for process industries to utilize clean natural gas for combustion. The refineries that can combust waste fuels typically have higher productivity and a relatively favorable competitive status compared to other refineries which are under utilizing the waste fuel potential.

[0008] With regard to NOx reduction, the common NOx control methods include utilization of low NOx burners equipped with higher levels of fuel staging and dilution of air/fuel with flue gas recirculation (FGR). By injecting non-reactive or inert chemical species in the fuel/oxidant mixture, the average flame temperature is reduced and thus, NOx emissions are reduced. However, these methods require additional piping and energy costs associated with the transport of flue gas. In addition, there is an energy penalty due to required heating of the gases from ambient temperature to the process temperature. In addition, the field data published in the literature do not indicate that these methods achieve less than 10 ppm NOx performance.

[0009] Various devices and methods using fuel staging have been developed with the goal of reducing NOx emissions. Several of these are discussed below.

[0010] U.S. Patent Application No. 2003/0148236 (Joshi, *et al.*) discloses an ultra low NOx burner using staged fuel nozzles. The burner has eight fuel staging lances located around the main burner body. The center part of the burner is used for supplying 100% of the combustion air and a very small amount of fuel (~ 10%) is injected for overall flame stability. The rest of the fuel (~ 90%) is injected using multiple fuel staging lances. The fuel staging lances have special fuel nozzle tips with two circular holes. As shown in Figures 1A-1C, these lances have axial and radial divergence angles for delayed mixing with the combustion air and entraining furnace gases due to a relatively high jet velocity (500 to 1,000 feet/sec or 5 to 15 psig fuel supply pressure depending on the firing rate).

[0011] U.S. Pat. No. 6,383,462 (Lang) discloses a method and an apparatus which has a mixing chamber outside of the "burner and furnace" for mixing flue gases from the furnace with the fuel gas, as shown in Figure 2. A converging diverging venturi mixer is utilized to further dilute the fuel gas with additional flow motivating gas. The resulting mixture (diluted fuel with flue gas) is then sent to the burner wherein the mixture is combined with the combustion air and burned in the furnace. Depending on the flue gas dilution level, a NOx emission reduction from 26 ppm to 14 ppm may be obtained. This apparatus and method do not reduce NOx emissions below 10 ppm and the results are not comparable to those typically achieved with SCR technology.

[0012] U.S. Pat. No. 6,481,209 (Johnson, *et al.*) discloses a fuel staging system suitable for gas turbine engines. Efficient combustion with air is achieved with lower NOx and CO emissions by splitting fuel injection in two stages: 1) injectors installed in swirl mixers, and 2) injectors installed in the trapped vortex region of the combustor. However, this injection scheme is not suitable for large furnaces where trapped vortex zones are not possible due to furnace and load geometry.

[0013] U.S. Pat. No. 6,558,154 (Eroglu, *et al.*) discloses a control based fuel staging strategy for an aero engine in which two separate instrumented fuel staging nozzles are used. A set of emission and pulsation sensors are installed downstream of each staging zone. These sensors measure the quality of combustion products issued from each staging zone and
5 then a control unit varies relative amounts of fuels injected in each zone depending on changing operating and environmental conditions.

[0014] U.S. Pat. No. 5,601,424 (Bernstein, *et al.*) discloses a method for reducing NOx using atomizing steam injection control. The NOx levels are lowered by adding to the burner flame atomizing steam, which is available for fuel oil atomization. For 30% NOx reduction,
10 approximately 0.5 lb steam/lb of fuel flow is necessary. A large amount of steam is necessary to reduce flame temperature and obtain a required NOx reduction. In addition, if a large amount of steam is used for flame quenching, there is a possibility of flame instability and sputtering. Thus, there is an upper limit for steam injection on flame stability grounds.

[0015] The gas turbine industry also uses a similar steam injection technique for NOx
15 control. However, due to an inefficient steam injection mode, a large economic penalty is paid in order to reduce NOx emissions. The steam consumption is very large, and the technique is relatively inefficient and not cost effective for NOx control.

[0016] It is desired to have a cost effective, retrofit apparatus and method for NOx emission reduction, which provide the ability to combust refinery waste gases without excessive NOx
20 emissions.

[0017] It is further desired to have an apparatus and method which reduce equipment maintenance due to problems such as plugging of burner tips and over-heating of process tubes, and which will provide additional benefits of improved fuel efficiency and furnace productivity.

[0018] It is still further desired to have an apparatus and method which will allow current low NOx burners to meet SCR level NOx performance and allow refiners to comply with NOx regulations without using the capital-intensive SCR technology.

[0019] It is still further desired to have an apparatus and method which will enable process industries to consume cheaper waste fuel without incurring penalties on maintenance issues such as tips plugging, equipment overheating, process interruptions, *etc.*, while at the same time meeting NOx regulations by producing less than 10 ppm NOx emissions.

[0020] It is also desired to have an apparatus and method for combusting a fuel which afford better performance than the prior art, and which also overcome many of the difficulties and disadvantages of the prior art to provide better and more advantageous results.

BRIEF SUMMARY OF THE INVENTION

[0021] The present invention is a method and a system for diluting a fuel to reduce nitrogen oxide emissions through fuel staging. The invention also includes a fuel dilution device that may be used in the method or the system.

[0022] There are multiple steps in a first embodiment of the method for diluting a fuel to reduce nitrogen oxide emissions through fuel staging. The first step is to provide a fuel dilution device, which includes: a first conduit having an inlet and an outlet spaced apart from the inlet, the first conduit adapted to transmit a stream of the fuel entering the inlet and exiting the outlet at a first thermodynamic state and a first fuel index; and a second conduit having an intake and an outtake spaced apart from the intake, the second conduit adapted to transmit a stream of a fluid entering the intake and exiting the outtake at a second thermodynamic state and a second fuel index, the second fuel index being different from the first fuel index by at least about 0.1 and the second thermodynamic state being different from the first thermodynamic state, whereby a potential for mixing exists between the stream of the fuel exiting the outlet of the first conduit and the stream of the fluid exiting the outtake of

the second conduit. The second step is to feed the stream of the fuel to the inlet of the first conduit, said stream of the fuel exiting the outlet of the first conduit at the first thermodynamic state and the first fuel index. The third step is to feed the stream of the fluid to the intake of the second conduit, said stream of the fluid exiting the outtake of the second conduit at the
5 second thermodynamic state and the second fuel index, whereby at least a portion of the stream of the fuel exiting the outlet of the first conduit mixes with at least a portion of the stream of the fluid exiting the outtake of the second conduit at a location proximate both the outlet and the outtake, thereby generating at least one diluted fuel stream having an intermediate fuel index between the first fuel index and the second fuel index. The fourth
10 step is to provide a source of an oxidant. The fifth step is to combust a portion of the oxidant with at least a portion of at least one of the stream of the fuel, or the stream of the fluid, or the diluted fuel stream, thereby generating a gas containing a reduced amount of nitrogen oxide, said reduced amount of nitrogen oxide being less than a higher amount of nitrogen oxide that would be generated by combusting the fuel using a means other than the fuel
15 dilution device.

[0023] There are many variations of the first embodiment of the method. In one variation, the fluid is a fuel. In another variation, the fluid is selected from a group consisting of steam, flue gas, carbon dioxide, nitrogen, argon, helium, xenon, krypton, other inert fluids, and mixtures or combinations thereof.

20 **[0024]** In another variation of the first embodiment of the method, the first conduit is adjacent the second conduit. In yet another variation, at least a substantial portion of the second conduit is disposed in the first conduit. In still yet another variation, the second conduit has an equivalent diameter (D_c) and the outtake of the second conduit is located at a distance behind the outlet of the first conduit, said distance being in a range of about ($2 D_c$) to about
25 ($20 D_c$).

[0025] A second embodiment of the method for diluting a fuel to reduce nitrogen oxide emissions through fuel staging is similar to the first embodiment but includes two additional steps. The first additional step is to provide a swirler disposed in the second conduit. The second additional step is to transmit at least a portion of the stream of the fluid through the
5 swirler, thereby swirling at least a portion of the fluid exiting the second conduit.

[0026] A third embodiment of the method is similar to the first embodiment, but includes two additional steps. The first additional step is to provide a zipper nozzle in fluid communication with the outlet of the first conduit. The second additional step is to transmit through the zipper nozzle at least a portion of a diluted fuel stream.

10 [0027] A fourth embodiment of the method is similar to the first embodiment but includes the additional step of placing the fuel dilution device in fluid communication with a furnace containing a quantity of a furnace gas, whereby at least a portion of the quantity of the furnace gas mixes with at least a portion of the diluted fuel stream.

[0028] Another embodiment of a method for diluting a fuel to reduce nitrogen oxide
15 emissions through fuel staging includes multiple steps. The first step is to provide a fuel dilution device, which includes: a first conduit having an inlet and an outlet spaced apart from the inlet, the first conduit adapted to transmit a stream of the fuel entering the inlet and exiting the outlet at a first pressure, a first velocity, and a first fuel index; and a second conduit having an intake and an outtake spaced apart from the intake, the second conduit
20 adapted to transmit a stream of a fluid entering the intake and exiting the outtake at a second pressure, a second velocity, and a second fuel index, the second fuel index being different from the first fuel index by at least about 0.1 and at least one of the second pressure and the second velocity being different from at least one of the first pressure and the first velocity, whereby a potential for mixing exists between the stream of the fuel exiting the outlet of the
25 first conduit and the stream of the fluid exiting the outtake of the second conduit. The second step is to feed the stream of the fuel to the inlet of the first conduit, said stream of the

fuel exiting the outlet of the first conduit at the first pressure, the first velocity, and the first fuel index. The third step is to feed the stream of the fluid to the intake of the second conduit, said stream of the fluid exiting the outtake of the second conduit at the second pressure, the second velocity, and the second fuel index, whereby at least a portion of the stream of the fuel exiting the outlet of the first conduit mixes with at least a portion of the stream of the fluid exiting the outtake of the second conduit at a location proximate both the outlet and the outtake, thereby generating at least one diluted fuel stream having an intermediate fuel index between the first fuel index and the second fuel index. The fourth step is to provide a source of an oxidant. The fifth step is to combust a portion of the oxidant with at least a portion of at least one of the stream of the fuel, or the stream of the fluid, or the diluted fuel stream, thereby generating a gas containing a reduced amount of nitrogen oxide, said reduced amount of nitrogen oxide being less than a higher amount of nitrogen oxide that would be generated by combusting the fuel using a means other than the fuel dilution device.

[0029] There are multiple elements in a first embodiment of a fuel dilution device for diluting a fuel to reduce nitrogen oxide emissions through fuel staging. The first element is a first conduit having an inlet and an outlet spaced apart from the inlet, the first conduit adapted to transmit a stream of a fuel entering the inlet and exiting the outlet at a first thermodynamic state and a first fuel index. The second element is a second conduit having an intake and an outtake spaced apart from the intake, the second conduit adapted to transmit a stream of a fluid entering the intake and exiting the outtake at a second thermodynamic state and a second fuel index, the second fuel index being different from the first fuel index by at least about 0.1 and the second thermodynamic state being different from the first thermodynamic state, whereby a potential for mixing exists between the stream of the fuel exiting the outlet of the first conduit and the stream of the fluid exiting the outtake of the second conduit, whereby at least a portion of the stream of the fuel exiting the outlet of the first conduit mixes

with at least a portion of the stream of the fluid exiting the outtake of the second conduit at a location proximate both the outlet and the outtake, thereby generating at least one diluted fuel stream having an intermediate fuel index between the first fuel index and the second fuel index. The third element is a source of an oxidant. The fourth element is a means for
5 combusting a portion of the oxidant with at least a portion of at least one of the stream of the fuel, or the stream of the fluid, or the diluted fuel stream, thereby generating a gas containing a reduced amount of nitrogen oxide, said reduced amount of nitrogen oxide being less than a higher amount of nitrogen oxide that would be generated by combusting the fuel using a means other than the fuel dilution device.

10 **[0030]** There are many variations of the first embodiment of the fuel dilution device. In one variation, the fluid is a fuel. In another variation, the fluid is selected from a group consisting of steam, flue gas, carbon dioxide, nitrogen, argon, helium, xenon, krypton, other inert fluids, and mixtures or combinations thereof.

[0031] In another variation, the first conduit is adjacent the second conduit. In yet another
15 variation, at least a substantial portion of the second conduit is disposed in the first conduit. In still yet another variation, the second conduit has an equivalent diameter (D_c) and the outtake of the second conduit is located at a distance behind the outlet of the first conduit, said distance being in a range of about ($2 \times D_c$) to about ($20 \times D_c$).

[0032] In another variation of the first embodiment, the fuel dilution device is in fluid
20 communication with a furnace containing a quantity of a furnace gas, whereby at least a portion of the quantity of the furnace gas mixes with at least a portion of the diluted fuel stream.

[0033] A second embodiment of the fuel dilution device is similar to the first embodiment but includes a swirler disposed in the second conduit. A third embodiment of the fuel dilution
25 device is similar to the first embodiment, but includes a zipper nozzle in fluid communication with the outlet of the first conduit.

[0034] Another embodiment of the fuel dilution device for diluting a fuel to reduce nitrogen oxide emissions through fuel staging includes multiple elements. The first element is a first conduit having an inlet and an outlet spaced apart from the inlet, the first conduit adapted to transmit a stream of a fuel entering the inlet and exiting the outlet at a first pressure, a first velocity, and a first fuel index. The second element is a second conduit having an intake and an outtake spaced apart from the intake, the second conduit adapted to transmit a stream of a fluid entering the intake and exiting the outtake at a second pressure, a second velocity, and a second fuel index, the second fuel index being different from the first fuel index by at least about 0.1 and at least one of the second pressure and the second velocity being different from at least one of the first pressure and the first velocity, whereby a potential for mixing exists between the stream of the fuel exiting the outlet of the first conduit and the stream of the fluid exiting the outtake of the second conduit, whereby at least a portion of the stream of the fuel exiting the outlet of the first conduit mixes with at least a portion of the stream of the fluid exiting the outtake of the second conduit at a location proximate both the outlet and the outtake, thereby generating at least one diluted fuel stream having an intermediate fuel index between the first fuel index and the second fuel index. The third element is a source of an oxidant. The fourth element is a means for combusting a portion of the oxidant with at least a portion of at least one of the stream of the fuel, or the stream of the fluid, or the diluted fuel stream, thereby generating a gas containing a reduced amount of nitrogen oxide, said reduced amount of nitrogen oxide being less than a higher amount of nitrogen oxide that would be generated by combusting the fuel using a means other than the fuel dilution device.

[0035] Another aspect of the invention is a system for diluting a fuel to reduce nitrogen oxide emissions through fuel staging. The system includes multiple elements. The first element is a fuel dilution device, which includes: a first conduit having an inlet and an outlet spaced apart from the inlet, the first conduit adapted to transmit a stream of the fuel entering the inlet

and exiting the outlet at a first thermodynamic state and a first fuel index; and a second conduit having an intake and an outtake spaced apart from the intake, the second conduit adapted to transmit a stream of a fluid entering the intake and exiting the outtake at a second thermodynamic state and a second fuel index, the second fuel index being different from the first fuel index by at least about 0.1 and the second thermodynamic state being different from the first thermodynamic state, whereby a potential for mixing exists between the stream of the fuel exiting the outlet of the first conduit and the stream of the fluid exiting the outtake of the second conduit. The second element is a means for feeding the stream of the fuel to the inlet of the first conduit, said stream of the fuel exiting the outlet of the first conduit at the first thermodynamic state and the first fuel index. The third element is a means for feeding the stream of the fluid to the intake of the second conduit, said stream of the fluid exiting the outtake of the second conduit at the second thermodynamic state and the second fuel index, whereby at least a portion of the stream of the fuel exiting the outlet of the first conduit mixes with at least a portion of the stream of the fluid exiting the outtake of the second conduit at a location proximate both the outlet and the outtake, thereby generating at least one diluted fuel stream having an intermediate fuel index between the first fuel index and the second fuel index. The fourth element is a source of an oxidant. The fifth element is a means for combusting a portion of the oxidant with at least a portion of at least one of the stream of the fuel, or the stream of the fluid, or the diluted fuel stream, thereby generating a gas containing a reduced amount of nitrogen oxide, said reduced amount of nitrogen oxide being less than the high amount of nitrogen oxide that would be generated by combusting the fuel using a means other than the fuel dilution device.

[0036] Another embodiment of the system for diluting a fuel to reduce nitrogen oxide emissions through fuel staging includes multiple elements. The first element is a fuel dilution device, which includes: a first conduit having an inlet and an outlet spaced apart from the inlet, the first conduit adapted to transmit a stream of the fuel entering the inlet and exiting

the outlet at a first pressure, a first velocity, and a first fuel index; and a second conduit having an intake and an outtake spaced apart from the intake, the second conduit adapted to transmit a stream of a fluid entering the intake and exiting the outtake at a second pressure, a second velocity, and a second fuel index, the second fuel index being different from the first fuel index by at least about 0.1 and at least one of the second pressure and the second velocity being different from at least one of the first pressure and the first velocity, whereby a potential for mixing exists between the stream of the fuel exiting the outlet of the first conduit and the stream of the fluid exiting the outtake of the second conduit. The second element is a means for feeding the stream of the fuel to the inlet of the first conduit, said stream of the fuel exiting the outlet of the first conduit at the first pressure, the first velocity, and the first fuel index. The third element is a means for feeding the stream of the fluid to the intake of the second conduit, said stream of the fluid exiting the outtake of the second conduit at the second pressure, the second velocity, and the second fuel index, whereby at least a portion of the stream of the fuel exiting the outlet of the first conduit mixes with at least a portion of the stream of the fluid exiting the outtake of the second conduit at a location proximate both the outlet and the outtake, thereby generating at least one diluted fuel stream having an intermediate fuel index between the first fuel index and the second fuel index. The fourth element is a source of an oxidant. The fifth element is a means for combusting a portion of the oxidant with at least a portion of at least one of the stream of the fuel, or the stream of the fluid, or the diluted fuel stream, thereby generating a gas containing a reduced amount of nitrogen oxide, said reduced amount of nitrogen oxide being less than a higher amount of nitrogen oxide that would be generated by combusting the fuel using a means other than the fuel dilution device.

BRIEF DESCRIPTION OF THE DRAWINGS

[0037] The invention will be described by way of example with reference to the accompanying drawings, in which:

5 [0038] Figure 1A is a cross-sectional plan view of a prior art fuel staging nozzle used in an ultra low-NO_x burner;

[0039] Figure 1B is a cross-sectional elevation view of the prior art fuel staging nozzle of Figure 1A;

[0040] Figure 1C is a side view of the prior art fuel staging nozzle of Figure 1B;

10 [0041] Figure 2 is a cross-sectional elevation view of a prior art mixing chamber for mixing flue gases from a furnace and a flow motivating gas with a fuel gas;

[0042] Figure 3 is a schematic diagram illustrating a cross-sectional view of one embodiment of the present invention;

[0043] Figure 4 is a schematic diagram illustrating a cross-sectional view of another
15 embodiment of the invention;

[0044] Figure 5A is a schematic diagram illustrating another embodiment of the invention which uses strong jet-weak jet entrainment;

[0045] Figure 5B is a schematic diagram illustrating a cross-sectional view of another embodiment of the invention which uses a swirl induced entrainment;

20 [0046] Figure 6 is a schematic diagram illustrating a cross-sectional view of another embodiment of the invention;

[0047] Figure 7 is a schematic diagram illustrating a cross-sectional view of another embodiment of the invention which includes a zipper tip or nozzle;

[0048] Figure 8A is a schematic diagram illustrating a front view of a zipper tip or nozzle;

25 [0049] Figure 8B is a schematic diagram illustrating a side view of a zipper tip or nozzle attached to a lance, such as that shown in Figure 7;

[0050] Figure 8C is a schematic diagram illustrating a plan view of a zipper tip or nozzle;

[0051] Figure 8D is a schematic diagram illustrating a portion of the front view of the zipper tip or nozzle in Figure 8A in detail for dimensioning; and

[0052] Figure 9 is a schematic diagram illustrating a cross-sectional view of another
5 embodiment of the invention which includes a zipper tip or nozzle.

DETAILED DESCRIPTION OF THE INVENTION

[0053] The present invention addresses a number of issues encountered in combustion
10 equipment design, such as burners used for heating reformers, process heaters, boilers, ethylene crackers, or other high temperature furnaces. The invention relates to an improved fuel staging process. In particular, two general approaches that provide for rapid dilution and mixing, depending on the required process objectives, are:

- I. Staging Fuel with Another Fuel (F-F): High-pressure refinery waste fuel, atomized
15 liquid fuel, *etc.* are injected in the vicinity of a relatively clean and low-pressure gaseous fuel for clean, maintenance free, low NOx operation; and
- II. Staging Fuel with Inert Gas (F-I): High-pressure inert fluids such as steam, nitrogen, CO2, *etc.* are injected in the vicinity of a low-pressure gaseous fuel for NOx reduction.

[0054] As used herein, the term "fuel index" (FI) is defined as the weighted sum of the fuel
20 carbon atom number where molecular H2 is assigned a carbon number 1.3, the weights being the component mole fractions: $FI = \sum C_i x_i / \sum x_i$, where C_i and x_i are the number of carbon atoms and the mole fraction of component i, respectively. The fuel indices of a number of fuels and inerts are listed in Table I. Generally, a fuel with a higher fuel index cracks more easily and produces more NOx through the prompt NOx mechanism. H2 is a
25 special case in this definition. Although H2 does not have any carbon atoms, it is well known that H2 addition in natural gas increases NOx emissions. The literature suggests that about a 30% higher NOx emission occurs for pure H2 flames as compared to methane flames.

The increased NO_x emission from H₂ flames is attributable to higher flame temperatures via the thermal NO_x mechanism. Since the fuel index is used as an indicator for NO_x emissions herein, a value of 1.3 is assigned to H₂ to be consistent with its NO_x emission potential.

Table I: Fuel Indices for Selected Fuels and Inerts

Fuels or Inerts	Fuel Index
H ₂	1.3
H ₂ O	0
CO ₂	0
CO	1
N ₂	0
CH ₄	1
C ₃ H ₈	3
ROG (1)	1.434
PSA offgas (2)	0.57
Natural gas (3)	1.08
Natural gas (4)	1.14

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(1) ROG: H₂ 18%, CH₄ 44%, C₂H₂ 38%.

(2) PSA offgas: H₂ 30%, CH₄ 18%, CO₂ 52%.

(3) Natural gas: CH₄ 91%, C₂H₆ 4%, C₃H₈ 3%, N₂ 1%, CO₂ 1%.

(4) Natural gas: CH₄ 84%, C₂H₆ 12%, C₃H₈ 2%, N₂ 2%.

- 10 **[0055]** As discussed herein, the term “thermodynamic state” is defined as a state of existence for a matter. This definition is based on the generally known concept of thermodynamics, but with an extension to include not only the usual temperature and pressure but also velocity, concentration, composition, volume fraction, flow rate, electric potential, *etc.*, to completely characterize a stream. This definition is used to precisely define
- 15 mixing as the result of a difference in the thermodynamic state between two streams.

[0056] The two approaches are discussed in detail below.

I. *Staging Fuel with Another Fuel (F-F):*

[0057] This approach may be used to combust refinery waste fuels at a high supply pressure that contain a blend of hydrogen and higher C/H fuels (ethane, propane, butane,

olefins, etc.) with a second relatively cleaner, low-pressure fuel gas. Maintenance problems arise with such refinery waste fuel due to thermal cracking of the high C/H fuels and subsequent soot build-up in the burner fuel tips. In addition, combustion of such fuels results in higher than normal NO_x emissions.

5 **[0058]** To improve combustion of high C/H refinery waste fuels, the dirty fuel is diluted with a relatively cleaner (secondary) fuel stream (e.g., hydrogen, syngas, natural gas, or a low BTU fuel blend). In one embodiment shown in Figure 3, a high-pressure refinery fuel gas (containing high C/H ratio fuel gases) is injected through a center lance 32 and a relatively clean, low-pressure fuel gas, such as natural gas, syngas, process gas, PSA off gas
10 (recycled fuel gas after removing product hydrogen from PSA adsorbent beds), etc is injected through an annular region 33 between the center lance 32 and an outer lance 34. As shown in Figure 3, the exit 36 of the center lance is recessed a preferred distance from the exit 38 of the outer lance. This distance preferably is 2 to 20 times the equivalent diameter (D_c) of the center lance. Depending on the fuel split between the high-pressure
15 refinery fuel gas and the cleaner low-pressure fuel gas, the distance preferably is about 1/16" to 1".

[0059] Persons skilled in the art will recognize that the reference to "high pressure" in Figures 3-7 and 9 also could state "high velocity" or "high pressure or high velocity." Similarly, the reference to "low pressure" in those figures could state "low velocity" or "low
20 pressure or low velocity."

[0060] The arrangement shown in Figure 3 allows the dirty high-pressure refinery fuel gas to mix with the cleaner low-pressure fuel gas due to turbulent jet interaction. The velocity of the high-pressure refinery fuel gas through the center lance 32 preferably is about 900 to 1400 feet/sec (preferably sonic or choked velocity). The velocity of the low-pressure fuel gas
25 through the annular region 33 between the center lance 32 and the outer lance 34 preferably is about 100 to 900 feet/sec, depending on the available supply pressure of the low-pressure

gas. The higher velocity gas stream exiting the exit 36 of the center lance entrains the lower velocity gas stream approaching the exit 38 of the outer lance and provides "first stage" mixing before the streams exit through an orifice(s) 40. The outer lance orifice geometry, angles, *etc.* are designed for optimum "second stage" mixing in the furnace atmosphere. A
5 very large amount of furnace gas 42 is entrained for second stage dilution, thereby lowering the peak flame temperatures and subsequent reduction in NOx emissions.

[0061] Figure 4 illustrates an arrangement for liquid fuel (F-F) staging. In this embodiment, a high-pressure (and high C/H ratio) liquid fuel (*e.g.*, fuel oil, diesel, bunker C, waste liquid fuel, *etc.*) is diluted using a low-pressure fuel gas before being injected into a furnace atmosphere
10 for further dilution. For example, heavy fuel oil can be atomized with an atomizing fluid, such as steam, and then diluted with a low-pressure fuel gas for soot free (clean) combustion inside the furnace. This embodiment also decreases NOx emissions due to lower peak flame temperatures.

[0062] In Figure 4, X is the distance from the exit of the center lance 32 to the back face of
15 the exit for the outer lance 34. D_c is the flow area-equivalent diameter of the exit of the center lance, that is, the total flow areas of the exit of the center lance is the same as a circle of diameter D_c . D_e is the flow area-equivalent diameter of the outer lance, that is, the total flow area of the exit of the lance is the same as a circle of diameter D_e .

[0063] Two other embodiments of (F-F) staging are shown in Figures 5A and 5B. In Figure
20 5A, a strong jet – weak jet interaction takes place between the high-pressure refinery fuel gas and the low-pressure fuel gas. The high-pressure refinery fuel gas is injected in a high-pressure lance 52 at a high velocity (about 900 to 1400 feet/sec) in a preferred direction, and a low-pressure fuel gas, which is injected in a low-pressure lance 54, is entrained by the high-pressure refinery fuel gas.

25 [0064] In Figure 5B, the high-pressure refinery fuel gas is swirled in a center lance 32 using a fuel swirler 56, and the low-pressure fuel gas is entrained in the collapsed region (central

region) of the high velocity swirl. This allows good mixing of the high-pressure refinery fuel gas and the low-pressure fuel gas before they exit the outer lance 34 and enter the furnace (not shown), where additional dilution takes place with the furnace gases 42. This approach is beneficial for applications requiring a short flame profile or a smaller combustion space.

5 **[0065]** An application for (F-F) staging is found in steam methane reformers (SMR) where the high-pressure fuel gas is generally a supply of natural gas or a refinery off-gas which is generally classified as a trim fuel. Referring to Figure 6, the high-pressure fuel gas is injected in the center lance 32. The low-pressure fuel gas injected in the annular region 33 between the center lance 32 and the outer lance 34 is generally PSA (pressure swing
10 adsorption) off-gas or clean vent stream from PSA that contains CO₂ (~45%), hydrogen (~30%), methane (~15%), and CO (~10%) with a fuel index of about 0.64. The PSA off-gas is permeate out of the adsorption bed after hydrogen product is separated. The high-pressure trim fuel accounts for between 10% to 30% of a total energy for typical reformers having PSA for hydrogen separation.

15 **[0066]** A secondary advantage of this staging application is to improve PSA recovery by increasing the range of PSA pressure cycle, particularly at the low end. Referring to Figure 7, this is achieved by creating a low-pressure region inside the outer lance 34. The high velocity central jet 72 shown in Figure 7 creates a low-pressure region around the jet body where the slower moving low-pressure fuel gas is entrained by the faster moving central jet.
20 Due to an active entrainment process, the supply pressure for the low-pressure fuel gas is reduced for the same fuel flow rate.

[0067] In one laboratory firing experiment, the supply pressure of low-pressure PSA off-gas was reduced from 2 psig to 1.6 psig (20% reduction). This was achieved by injecting the high- pressure fuel gas at 25 psig (1300 feet/sec velocity). The combustion energy split
25 between the high-pressure fuel gas and the low-pressure fuel gas was 30:70 respectively.

[0068] To further quantify details of the (F-F) staging process, laboratory test results were considered using a low NOx burner. The burner had 10 fuel lances distributed around a circle of 18" diameter. Of the 10 fuel lances, two lances were reserved for the (F-F) type staging configuration. The lances had special fuel tips and multiple diverging slots (zipper tips 74) to improve passive mixing. A schematic diagram of the (F-F) fuel staging configuration using zipper tips 74 is shown in Figure 7. The burner was rated at 8 MM Btu/hr firing rate utilizing 644°F air preheat and it was designed to utilize two types of fuels. The details of the two fuels are provided below:

- High-pressure refinery fuel gas: H₂ (18%), natural gas (44%) and ethylene (38%). This fuel has a fuel index of 1.43 and accounts for 30% of the total energy input.
- Low-pressure fuel gas: CO₂ (52%), natural gas (18%) and H₂ (30). It has a fuel index of 0.57, and accounts for about 70% of the total energy input.

[0069] Referring to the arrangement illustrated in Figure 7, the high-pressure fuel gas was injected in a center lance 32 made of standard tubing having a 3/8" diameter x 0.035" wall thickness, which was placed concentrically in an outer lance 34 made of pipe of 3/4" sch 40. A zipper tip 74 was attached to the end of the pipe. The zipper tip was sized for 0.51" equivalent diameter and, as shown in Figures 8A-8D, had four vertical slots and one horizontal slot. The divergence angles (α_1 and α_2) for the vertical slots were 18° and 6° respectively for the axial zipper nozzle tip geometry as follows: 1) a series of vertical structures at intersecting planes between adjacent primary shapes; 2) flow induced downstream instabilities; and 3) a high level of molecular (small-scale) mixing between the first fluid (fuels) and the second fluid (furnace gases). The above mixing also was achieved in the shortest axial distance. The low NOx burner laboratory experiments conducted with

the lance-in-lance configuration of Figure 7 (including zipper tips), indicate a rapid axial mixing, higher furnace gas entrainment with the divergence angle β at 7° .

5 **[0070]** The overall fluid processes according to the arrangement of Figure 7 resulted in more uniform heat transfer to the load and ultra low (< 15 ppmv) NO_x and CO emissions at a fuel pressure less than 2 psig. It was also noticed that without the lance-in-lance process, the combustion of high pressure and high C/H ratio fuel produces a visible soot rich flame. Also, the NO_x emissions were as high as 25 to 30 ppm. This experiment demonstrated that the F-F staging process could lower NO_x emissions dramatically. The F-I staging process could reduce the emissions even more with inerts.

10 **[0071]** The visual proof of enhanced mixing was observed in a furnace in a laboratory whenever the lance-in-lance (F-F) fuel staging configuration was used for refinery fuels consisting of butane (C₄H₁₀) as high as 50%. The individual flames were found to mix much more quickly with furnace gases and created a spacious or flameless combustion. On the other hand, simple lances with cylindrical nozzle lances created a rather visible (bluish) and
15 relatively longer flame, indicating less furnace gas dilution and mixing, and at the same time produced relatively higher NO_x and CO emission levels at given fuel supply pressure.

20 **[0072]** Table II provides a preferred firing range, dimensions, dimensionless ratios and injection angles for a proposed lance-in-lance configuration. Simple circular tubing was used for high-pressure refinery fuel whereas a zipper tip was used for the low-pressure PSA off-gas fuel. These lances are critical components of a low NO_x burner because the reliability of burner performance directly affects steam methane reformer on stream performance.

Table II: Dimensional parameters for Lance-in-Lance fuel staging tips

	Low pressure zipper tip							High Prs. Cyl. Tip	
	(H)	(W)	(R _o /R _i)	(H/R _o)	(α1, α2)	(β)	L/D _e	D _c	X/D _c
Burner Firing Capacity (MM Btu/Hr)	Slot Height (In)	Slot Width (In)	Slot end radius to center radius ratio	Slot height to corner radius ratio	Axial div. Angle (°)	Radial div. Angle (°)	Zipper tip thickness to equiv. diameter ratio	Tube Dia (inch)	Dist. back zipper tip inlet
8	(1/32 – 1)	(1/4 -2)	1.6 (1 – 3)	3.7 (2 – 6)	15 (0 – 30)	7 (0– 30)	0.625 (0.05-3)	0.305 (1/16 – 2)	4 (2-20)
5.2	(1/32 – 1)	(1/4 -2)	1.6 (1 – 3)	3.7 (2 – 6)	15 (0 – 30)	7 (0 –30)	0.625 (0.05-3)	0.277 (1/16 – 2)	4 (2 – 10)

[0073] The above dimensional ranges are valid for a variety of fuels, such as natural gas, propane, refinery off gases, low BTU fuels, *etc.* The nozzles are optimally sized depending on fuel composition, flow rate (or firing rate) and supply pressure available at the burner inlet. In Table II, the dimensions, ratios and ranges are estimated for a 2 to 10 MM Btu/Hr burner firing rate. However, these dimensions and ranges can be scaled up for higher firing rate burners (> 10 MM Btu/Hr) using standard engineering practice of keeping similar flow velocity ranges.

10 II. Staging Fuel with Inert Gas (F-I):

[0074] The improved fuel staging with high-pressure inert gases, such as steam (dry or saturated, CO₂, flue gas, nitrogen, or other inert gases, is performed with low-pressure fuel gases to reduce NO_x emissions. The staging fuels that may be used include but are not limited to natural gas; low BTU process gas (consisting of hydrogen and other refinery fuels); and PSA off-gas. The injection tip configurations are similar to those shown in Figures 3-7. The main objective is to further reduce NO_x emissions. A preferred embodiment is illustrated in Figure 9.

[0075] Referring to Figure 9, a high pressure (30 to 100 psig) saturated or dry steam is sent through the center lance 32 at about 900 to 1400 feet/sec and low-pressure fuel gas is sent through the annular region 33 between the center lance 32 and the outer lance 34. A high velocity steam jet 92 entrains the fuel gas for first stage dilution (and mixing) inside the annular region. The resulting mixture then exits through a zipper tip 74 at a high velocity (about 600 to 1400 feet/sec) for second stage dilution in the furnace (not shown) using furnace gases (not shown). The second stage dilution is very effective due to high steam velocities and entrainment loops set up by individual flames formed by the zipper tip. Due to the zipper tip geometry and steam-assist, improved fuel dilution is obtained. The peak flame temperatures are further reduced and ultra low NOx emissions are obtained. Table III provides estimated steam consumption numbers for a large steam methane reformer furnace.

Table III: Steam Consumption Economics with Proposed (F-I) Staging Process

steam injection rate	lb_stm/lb_fuel	0.02	0.05
firing rate	mmbtu/hr LHV	850	850
fuel heating value	btu/scf, LHV	1000	1000
fuel cost	\$/mmbtu, LHV	6	6
fuel molecular weight		18	18
steam needed	lb/hr	806	2,016
	mmscfd	0.408	1.02
energy required to generate steam at 100 psia and 400 F from water at 60 F	btu/scf	57.1	57.1
	btu/lb	1203.2	1203.2
steam cost	\$/day	140	349
	\$/year	50,992	127,480

[0076] As shown in Table III, due to the unique method of fuel staging with an inert gas such as steam, the amount of steam required for fuel dilution is extremely low. The amount of

steam needed for (F-I) staging is from about 2% to 10% on a lb per lb basis when compared to the low-pressure fuel. The high velocity of steam is used for a two-stage dilution process:

1) inside the lance tube using steam and low-pressure fuel gas, and 2) in the furnace space using high velocity fuel-steam mixture and furnace gases.

5 **[0077]** The laboratory experiments using an inert gas, such as nitrogen, have shown that NO_x reductions of about 30% to 40% are possible based on a comparison between the simple prior art lance configuration (zipper or circular tips alone without lance-in-lance arrangement) and the lance-in-lance configuration of Figure 9. For example, using a low NO_x burner, at 5 MM btu/Hr firing rate, using ambient combustion air, a furnace operating at
10 an average temperature of 1600°F, exhaust gas at 2000°F, using a nitrogen flow rate of 10% on a weight basis, the NO_x emission is reduced from about 10 ppm (corrected at 3% O₂) for no inert gas in the center to about 7 ppm (corrected at 3% O₂) with nitrogen gas in the center.

[0078] In each of the embodiments discussed above, the favorable results achieved by the
15 present invention are driven by two differences in the streams exiting the two conduits. The first difference is a difference in the thermodynamic states of the respective streams, and the second difference is a difference in the fuel indices of the respective streams. Specifically, in order for there to be a potential for mixing between the two streams exiting the two conduits, there must be a difference in the thermodynamic states of the two streams, and a difference
20 of at least 0.1, and preferably at least 0.2, between the fuel indices of the two streams must exist for meaningful NO_x reduction.

[0079] In the embodiments illustrated in the figures and discussed above, the difference between the thermodynamic states of the two streams is expressed in terms of the pressure differential (*i.e.*, a "high pressure" fluid in one conduit, and a "low pressure" fluid in the other
25 conduit). However, persons skilled in the art will recognize that the differential in thermodynamic states may also be expressed in terms of, and achieved as a result of,

differences in velocity, temperature, concentration, composition, volume fraction, flow rate, electric potential, *etc.*

[0080] Therefore, the present invention includes many other embodiments and variations thereof which are not illustrated in the figures or discussed in the Detailed Description of The Invention. Those embodiments and variations, however, do fall within the scope of the appended claims and equivalents thereof.

[0081] Those skilled in the art also will recognize that the embodiments and variations illustrated in the drawings and discussed in the Detailed Description of The Invention do not disclose all of the possible arrangements of the present invention, and that other arrangements are possible. Accordingly, all such other arrangements are contemplated by the present invention and are within the scope of the present invention. For example, in each of the embodiments illustrated in Figures 3-7 and 9, the arrangement of the low pressure and high pressure streams may be reversed (*i.e.*, the low pressure lance may be the inner lance, and the high pressure lance may be the outer lance).

[0082] In addition to reduced NOx emissions, there are other advantages and benefits of the present invention, some of which are discussed below:

- The proposed fuel staging method enables active tip cooling due to either (F-F) staging or (F-I) staging. For fuel tips having relatively large tip exit area, the nozzle tips are actively cooled by exiting high velocity fuel gas or inert stream. This is a significant improvement over conventional circular nozzles.
- Due to relatively poor entrainment efficiency and higher operating temperature, conventional tips have serious maintenance issues and soot plugging problems using high C/H fuels. In comparison the present invention has the following advantages:

- reduced tendency to coke while using higher carbon content fuels
- ability to use smaller flow rates or higher heating value fuels
- ability to use cheaper fuel nozzle material (Stainless steel 304 or 310 is adequate)

5

[0083] Thermal cracking is a main concern for many refinery furnaces where fuel compositions contain hydrocarbons ranging from C1 to C4. The cracked carbon is found to plug burner nozzles and create over heating of burner parts, reduced productivity and poor thermal efficiency. Thus, having maintenance free operation (using F-F or F-I staging) is a

10 critical advantage for the refinery operator.

[0084] Although illustrated and described herein with reference to certain specific embodiments, the present invention is nevertheless not intended to be limited to the details shown. Rather, various modifications may be made in the details within the scope and range of equivalents of the claims and without departing from the spirit of the invention.

CLAIMS

1. A method for diluting a fuel to reduce nitrogen oxide emissions through fuel staging, comprising the steps of:

providing a fuel dilution device, the fuel dilution device comprising

a first conduit having an inlet and an outlet spaced apart from the inlet, the first conduit adapted to transmit a stream of the fuel entering the inlet and exiting the outlet at a first thermodynamic state and a first fuel index, and

a second conduit having an intake and an outtake spaced apart from the intake, the second conduit adapted to transmit a stream of a fluid entering the intake and exiting the outtake at a second thermodynamic state and a second fuel index, the second fuel index being different from the first fuel index by at least about 0.1 and the second thermodynamic state being different from the first thermodynamic state, whereby a potential for mixing exists between the stream of the fuel exiting the outlet of the first conduit and the stream of the fluid exiting the outtake of the second conduit;

feeding the stream of the fuel to the inlet of the first conduit, said stream of the fuel exiting the outlet of the first conduit at the first thermodynamic state and the first fuel index;

feeding the stream of the fluid to the intake of the second conduit, said stream of the fluid exiting the outtake of the second conduit at the second thermodynamic state and the second fuel index,

whereby at least a portion of the stream of the fuel exiting the outlet of the first conduit mixes with at least a portion of the stream of the fluid exiting

the outtake of the second conduit at a location proximate both the outlet and the outtake, thereby generating at least one diluted fuel stream having an intermediate fuel index between the first fuel index and the second fuel index;

providing a source of an oxidant; and

combusting a portion of the oxidant with at least a portion of at least one of the stream of the fuel, or the stream of the fluid, or the diluted fuel stream, thereby generating a gas containing a reduced amount of nitrogen oxide, said reduced amount of nitrogen oxide being less than a higher amount of nitrogen oxide that would be generated by combusting the fuel using a means other than the fuel dilution device.

2. A method as in claim 1, wherein the fluid is a fuel.

3. A method as in claim 1, wherein the fluid is selected from a group consisting of steam, flue gas, carbon dioxide, nitrogen, argon, helium, xenon, krypton, other inert fluids, and mixtures or combinations thereof.

4. A method as in claim 1, wherein the first conduit is adjacent the second conduit.

5. A method as in claim 1, wherein at least a substantial portion of the second conduit is disposed in the first conduit.

6. A method as in claim 1, comprising the further steps of:
providing a swirler disposed in the second conduit; and
transmitting at least a portion of the stream of the fluid through the

swirler, thereby swirling at least a portion of the fluid exiting the second conduit.

7. A method as in claim 1, comprising the further steps of:
providing a zipper nozzle in fluid communication with the outlet of the first conduit; and
transmitting through the zipper nozzle at least a portion of the diluted fuel stream.

8. A method as in claim 1, wherein the second conduit has an equivalent diameter (D_c) and the outtake of the second conduit is located at a distance behind the outlet of the first conduit, said distance being in a range of about ($2 \times D_c$) to about ($20 \times D_c$).

9. A method as in claim 1, comprising the further step of placing the fuel dilution device in fluid communication with a furnace containing a quantity of a furnace gas, whereby at least a portion of the quantity of the furnace gas mixes with at least a portion of the diluted fuel stream.

10. A method for diluting a fuel to reduce nitrogen oxide emissions through fuel staging, comprising the steps of:

providing a fuel dilution device, the fuel dilution device comprising
a first conduit having an inlet and an outlet spaced apart from the inlet, the first conduit adapted to transmit a stream of the fuel entering the inlet and exiting the outlet at a first pressure, a first velocity, and a first fuel index, and
a second conduit having an intake and an outtake spaced

apart from the intake, the second conduit adapted to transmit a stream of a fluid entering the intake and exiting the outtake at a second pressure, a second velocity, and a second fuel index, the second fuel index being different from the first fuel index by at least about 0.1 and at least one of the second pressure and the second velocity being different from at least one of the first pressure and the first velocity, whereby a potential for mixing exists between the stream of the fuel exiting the outlet of the first conduit and the stream of the fluid exiting the outtake of the second conduit;

feeding the stream of the fuel to the inlet of the first conduit, said stream of the fuel exiting the outlet of the first conduit at the first pressure, the first velocity, and the first fuel index;

feeding the stream of the fluid to the intake of the second conduit, said stream of the fluid exiting the outtake of the second conduit at the second pressure, the second velocity, and the second fuel index,

whereby at least a portion of the stream of the fuel exiting the outlet of the first conduit mixes with at least a portion of the stream of the fluid exiting the outtake of the second conduit at a location proximate both the outlet and the outtake, thereby generating at least one diluted fuel stream having an intermediate fuel index between the first fuel index and the second fuel index;

providing a source of an oxidant; and

combusting a portion of the oxidant with at least a portion of at least one of the stream of the fuel, or the stream of the fluid, or the diluted fuel stream, thereby generating a gas containing a reduced amount of nitrogen oxide, said reduced amount of nitrogen oxide being less than a higher

amount of nitrogen oxide that would be generated by combusting the fuel using a means other than the fuel dilution device.

11. A fuel dilution device for diluting a fuel to reduce nitrogen oxide emissions through fuel staging, comprising:

a first conduit having an inlet and an outlet spaced apart from the inlet, the first conduit adapted to transmit a stream of a fuel entering the inlet and exiting the outlet at a first thermodynamic state and a first fuel index; and

a second conduit having an intake and an outtake spaced apart from the intake, the second conduit adapted to transmit a stream of a fluid entering the intake and exiting the outtake at a second thermodynamic state and a second fuel index, the second fuel index being different from the first fuel index by at least about 0.1 and the second thermodynamic state being different from the first thermodynamic state, whereby a potential for mixing exists between the stream of the fuel exiting the outlet of the first conduit and the stream of the fluid exiting the outtake of the second conduit,

whereby at least a portion of the stream of the fuel exiting the outlet of the first conduit mixes with at least a portion of the stream of the fluid exiting the outtake of the second conduit at a location proximate both the outlet and the outtake, thereby generating at least one diluted fuel stream having an intermediate fuel index between the first fuel index and the second fuel index;

a source of an oxidant; and

means for combusting a portion of the oxidant with at least a portion of at least one of the stream of the fuel, or the stream of the fluid, or the diluted fuel stream, thereby generating a gas containing a reduced amount of nitrogen oxide, said reduced amount of nitrogen oxide being less than a

higher amount of nitrogen oxide that would be generated by combusting the fuel using a means other than the fuel dilution device.

12. A fuel dilution device as in claim 11, wherein the fluid is a fuel.

13. A fuel dilution device as in claim 11, wherein the fluid is selected from a group consisting of steam, flue gas, carbon dioxide, nitrogen, argon, helium, xenon, krypton, other inert fluids, and mixtures or combinations thereof.

14. A fuel dilution device as in claim 11, wherein the first conduit is adjacent the second conduit.

15. A fuel dilution device as in claim 11, wherein at least a substantial portion of the second conduit is disposed in the first conduit.

16. A fuel dilution device as in claim 11, further comprising a swirler disposed in the second conduit.

17. A fuel dilution device as in claim 11, further comprising a zipper nozzle in fluid communication with the outlet of the first conduit.

18. A fuel dilution device as in claim 11, wherein the second conduit has an equivalent diameter (D_c) and the outtake of the second conduit is located at a distance behind the outlet of the first conduit, said distance being in a range of about ($2 \times D_c$) to about ($20 \times D_c$).

19. A fuel dilution device as in claim 11, wherein the fuel dilution device is in fluid communication with a furnace containing a quantity of a furnace gas, whereby at least a portion of the quantity of the furnace gas mixes with at least a portion of the diluted fuel stream.

20. A fuel dilution device for diluting a fuel to reduce nitrogen oxide emissions through fuel staging, comprising:

a first conduit having an inlet and an outlet spaced apart from the inlet, the first conduit adapted to transmit a stream of a fuel entering the inlet and exiting the outlet at a first pressure, a first velocity, and a first fuel index; and

a second conduit having an intake and an outtake spaced apart from the intake, the second conduit adapted to transmit a stream of a fluid entering the intake and exiting the outtake at a second pressure, a second velocity, and a second fuel index, the second fuel index being different from the first fuel index by at least about 0.1 and at least one of the second pressure and the second velocity being different from at least one of the first pressure and the first velocity, whereby a potential for mixing exists between the stream of the fuel exiting the outlet of the first conduit and the stream of the fluid exiting the outtake of the second conduit,

whereby at least a portion of the stream of the fuel exiting the outlet of the first conduit mixes with at least a portion of the stream of the fluid exiting the outtake of the second conduit at a location proximate both the outlet and the outtake, thereby generating at least one diluted fuel stream having an intermediate fuel index between the first fuel index and the second fuel index;

a source of an oxidant; and

means for combusting a portion of the oxidant with at least a portion of at least one of the stream of the fuel, or the stream of the fluid, or the diluted fuel stream, thereby generating a gas containing a reduced amount of nitrogen oxide, said reduced amount of nitrogen oxide being less than a higher amount of nitrogen oxide that would be generated by combusting the fuel using a means other than the fuel dilution device.

21. A system for diluting a fuel to reduce nitrogen oxide emissions through fuel staging, comprising:

a fuel dilution device, the fuel dilution device comprising

a first conduit having an inlet and an outlet spaced apart from the inlet, the first conduit adapted to transmit a stream of the fuel entering the inlet and exiting the outlet at a first thermodynamic state and a first fuel index, and

a second conduit having an intake and an outtake spaced apart from the intake, the second conduit adapted to transmit a stream of a fluid entering the intake and exiting the outtake at a second thermodynamic state and a second fuel index, the second fuel index being different from the first fuel index by at least about 0.1 and the second thermodynamic state being different from the first thermodynamic state, whereby a potential for mixing exists between the stream of the fuel exiting the outlet of the first conduit and the stream of the fluid exiting the outtake of the second conduit;
means for feeding the stream of the fuel to the inlet of the first

conduit, said stream of the fuel exiting the outlet of the first conduit at the first thermodynamic state and the first fuel index;

means for feeding the stream of the fluid to the intake of the second conduit, said stream of the fluid exiting the outtake of the second conduit at the second thermodynamic state and the second fuel index,

whereby at least a portion of the stream of the fuel exiting the outlet of the first conduit mixes with at least a portion of the stream of the fluid exiting the outtake of the second conduit at a location proximate both the outlet and the outtake, thereby generating at least one diluted fuel stream having an intermediate fuel index between the first fuel index and the second fuel index;

a source of an oxidant; and

means for combusting a portion of the oxidant with at least a portion of at least one of the stream of the fuel, or the stream of the fluid, or the diluted fuel stream, thereby generating a gas containing a reduced amount of nitrogen oxide, said reduced amount of nitrogen oxide being less than a higher amount of nitrogen oxide that would be generated by combusting the fuel using a means other than the fuel dilution device.

22. A system for diluting a fuel to reduce nitrogen oxide emissions through fuel staging, comprising:

a fuel dilution device, the fuel dilution device comprising

a first conduit having an inlet and an outlet spaced apart from the inlet, the first conduit adapted to transmit a stream of the fuel entering the inlet and exiting the outlet at a first pressure, a first velocity, and a first fuel index, and

a second conduit having an intake and an outtake spaced apart from the intake, the second conduit adapted to transmit a stream of a fluid entering the intake and exiting the outtake at a second pressure, a second velocity, and a second fuel index, the second fuel index being different from the first fuel index by at least about 0.1 and at least one of the second pressure and the second velocity being different from at least one of the first pressure and the first velocity, whereby a potential for mixing exists between the stream of the fuel exiting the outlet of the first conduit and the stream of the fluid exiting the outtake of the second conduit;

means for feeding the stream of the fuel to the inlet of the first conduit, said stream of the fuel exiting the outlet of the first conduit at the first pressure, the first velocity, and the first fuel index;

means for feeding the stream of the fluid to the intake of the second conduit, said stream of the fluid exiting the outtake of the second conduit at the second pressure, the second velocity, and the second fuel index,

whereby at least a portion of the stream of the fuel exiting the outlet of the first conduit mixes with at least a portion of the stream of the fluid exiting the outtake of the second conduit at a location proximate both the outlet and the outtake, thereby generating at least one diluted fuel stream having an intermediate fuel index between the first fuel index and the second fuel index;

a source of an oxidant; and

means for combusting a portion of the oxidant with at least a portion of at least one of the stream of the fuel, or the stream of the fluid, or the diluted fuel stream, thereby generating a gas containing a reduced amount of nitrogen oxide, said reduced amount of nitrogen oxide being less than a

higher amount of nitrogen oxide that would be generated by combusting the fuel using a means other than the fuel dilution device.