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Low NO_x burner.

A method of operating a burner to reduce the NO_x emissions produced thereby is disclosed. Air and gas are premixed in a manner such that excess air exists in the resulting mixture and the velocity of the mixture is increased as it passes through the burner. By increasing the velocity of the air/gas mixture, the "residence time" associated with the formation of the flame is decreased, i.e., the combustion gases are in the reaction zone of the flame for a significantly shorter period of time, reducing the production of NO_x. In order to prevent the flame from "lifting-off" the burner because of the high velocity of the air/gas mixture, flame stabilizing devices or techniques are utilized resulting in a high heat flux and low NO_x production.

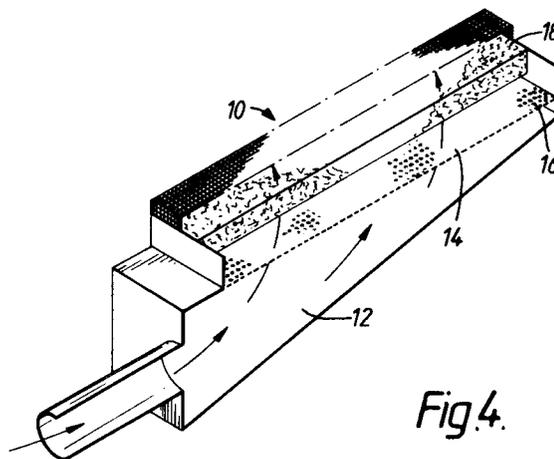


Fig. 4.

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The present invention relates, in general, to combustion apparatus and, more particularly, to a combustion technique that produces an extremely low level of NO_x emissions.

BACKGROUND ART

Recently, there has been a great deal of concern over the problem of air pollution. This problem is particularly acute in the urban areas of the country. There are many sources of air pollution such as the internal combustion engine, chemical processing plants, power generating facilities, etc. One of the more serious pollutants is the oxides of nitrogen, such as NO and NO₂, which are collectively known as NO_x and which contribute to air pollution by the formation of smog.

In fuel burning facilities, such as power generating stations, there are various sources of NO_x emissions. One source of NO_x emissions, referred to as thermal NO, results from the oxidation of the nitrogen (N₂) component of the combustion process air. Thermochemistry requires temperatures in the order of 2800°F. for the formation of NO in this manner. The diatomic nitrogen (N₂) component must first be dissociated into atomic nitrogen (N) prior to the formation of NO. Another source of NO_x emissions, referred to as fuel NO, results from the fact that many fuels contain the single atomic nitrogen species, for example, ammonia (NH₃). In this case, N₂ bond splitting is not a prerequisite to NO formation thereby allowing conversion of fuel-bound N to NO at temperature significantly below 2800°F. Conversion of fuel-bound nitrogen to NO can occur at temperatures as low as 1300°F. A still another source of NO_x emissions, referred to as prompt NO, results from high-speed reactions. Formation of NO by high speed reactions within the flame front have been reported and is the subject of ongoing research. No widely accepted mechanism for this mechanism has been developed. In those geographic areas where stringent air quality control regulations have been enacted, such as in Southern California, it has become extremely difficult to reach the standards established for NO_x emissions by utilizing presently available burners and/or methods of operating same.

Various approaches have been developed for reducing NO_x emissions, however, the resulting reduction is not sufficient in many cases to satisfy the foregoing stringent air quality standards. Some of these approaches are based on reducing NO_x emissions by multi-stage combustion. For example, such multi-stage combustion might involve burning a first fuel as a "lean mixture" and subsequently burning the resulting combustion products with a second fuel to form an atmosphere which causes a reduction in NO_x emissions. Alternatively, fuel and

air can be introduced into a burner so as to form two separate streams each having different ratios of fuel to air, i.e., one stream would have an excess of air while the other stream would have an excess of fuel. One of the streams is then ignited effecting a first stage of combustion which then ignites the second stream effecting a second stage of combustion. A third stage of combustion is provided by mixing and burning the excess fuel in one of the streams with the excess air in the other of the streams. A still another approach to reduce NO_x emissions requires a plurality of burners disposed in a series connection with respect to the direction of flow of combustion air. In this case, the last burner in the series of burners utilizes a fuel having lower NO_x producing properties.

Decreasing the temperature of combustion can also result in a reduction in NO_x emissions. The combustion temperature can be reduced by direct flame cooling through water injection of the combustion gases or by adding a cooling gas to the air-gas mixture. Flame temperature can also be reduced by utilizing radiant burners which are essentially surface burners often employing ceramic fibers, metallic fibers or reticulated ceramic foams as the radiant surface. A major disadvantage of most surface combustors is that because of their large size, a substantial volume of air/gas mixture is trapped within the burner. In the event of flashback, which is a distinct possibility, the deflagration created may be of explosive proportions. Another disadvantage of surface combustors is that to achieve optimal radiant output for a given input (radiant efficiency), the surface temperature must remain extremely high. Surface combustion temperatures are very sensitive to air/fuel ratio, velocity, and flow uniformity. A reduction in surface temperature diminishes the radiant output by the fourth power which would likely result in higher NO_x emissions levels, via higher flame temperatures.

NO_x emissions can also be reduced by recirculating the flue gases within the combustion chamber. In this approach, a portion of the flue gases can either be mixed with the combustion air prior to combustion, or delivered into the combustion zone separately. The recirculated flue gas acts as a diluent to lower the overall oxygen concentration and flame temperature. In essence, the combustion air supply is vitiated, thus reducing NO_x, however, carbon monoxide (CO) emissions might increase.

Another approach for reducing the production of NO_x involves changing the composition of the air-gas mixture. For example, if a mixture of oxygen and an inert gas, other than nitrogen, is utilized as the combustion atmosphere, NO_x emissions are reduced. Alternatively, an additive can be introduced into the combustion chamber to form reduc-

ing agents which react with the nitrogen oxides to produce nitrogen, thus reducing the production of NO_x . Thus, there are many approaches for reducing NO_x emissions.

All of the foregoing approaches for reducing NO_x emissions have certain inherent disadvantages with respect to cost, reliability, performance, etc. For example, reducing the combustion temperature to reduce the production of NO_x may result in a reduction in the heat flux produced by the burner. Multi-stage combustion requires a significant amount of equipment and associated controls, all of which can become quite costly. Similarly, flue gas recirculation techniques require additional equipment and might increase the production of carbon monoxide (CO), whereas the use of additives increases operating cost. Radiant process fibrous materials are expensive, often fragile, and sensitive to blockage from airborne dust, thus requiring filtration equipment and associated maintenance. Such air filtration equipment will not prevent burner plugging problems inherent in the combustion of numerous fuel gases which contain contaminants, such as tar.

It is well established that thermal NO formation is the predominant NO_x producing mechanism in the combustion of clean fuels, e.g., natural gas, and that the Zeldovich chain reaction mechanism applies to thermal NO formation. The chemical reaction kinetics of this analytical model predict that NO_x production increases with time and temperature. These trends have been verified in practical combustion systems with peak NO_x formation rates occurring slightly to the fuel lean side of stoichiometric. Predictions of the relative contributions of time and temperature in the formation of NO using the Zeldovich chain reaction model are illustrated in Figure 1. This Figure also illustrates the contribution of "residence time" to the formation of NO_x , i.e., the production of NO_x takes a finite period of time. Figure 1 illustrates the importance of "residence time" in the formation of NO_x as calculated using the Zeldovich chain reaction model. At a flame temperature of 3400°F ., "residence times" of 0.1, 0.7 and 4.5 seconds produce NO_x levels of 100 ppmv, 1000 ppmv and equilibrium levels, respectively, all of which exceed proposed emissions standards.

Reducing the combustion reaction (flame) temperature by using an excess of combustion air can, in certain cases, result in lower NO_x formation. This effect can only be used to significant advantage with a homogeneous pre-mix type combustion apparatus; in chemical parlance, a plug flow reactor. In the plug flow method, the peak fuel to air concentration equals the average concentration due to the premixing. This results in the average flame temperature being equal to the peak flame tem-

perature. The NO_x emissions are then proportional to this temperature level. In a nozzle mixing burner (stirred reactor), the mixing and combustion reactions occur virtually simultaneously, and due to mixing imperfections, wide variations in fuel to air concentrations occur. This results in mixture stratification with some localized peak fuel to air concentrations significantly in excess of the overall average value. Where the higher concentrations occur, high temperatures result, with concurrent high levels of NO_x formation.

Pre-mix combustion systems also offer the advantage of a high heat release rate per unit of combustion volume as compared to nozzle mix systems. In other respects, they are inferior to nozzle mixing systems; particularly with respect to combustion stability limits. Beyond certain air to fuel ratio values, combustion moves away from the burner apparatus and the flame is extinguished. These effects are apparent in Figure 2, in which it can be seen that pre-mix burners have a limited stability range in the more useful fuel lean non-polluting operating range. Also, for all burner types, as the stability limits are approached, the combustion efficiency decreases prior to flame extinction or "blow-out". The reduction in combustion efficiency produces large amounts of unburned combustible pollutants, predominately CO in the case of natural gas combustion.

In addressing the NO_x problem, it is necessary that NO_x and CO be considered simultaneously, because a reduction in one pollutant may merely represent a compromise with regard to emissions of the other. For most conventional burners, CO and NO_x emissions are generally produced in inverse proportions. Whereas the elimination of carbonaceous pollutants, e.g., CO, etc., is amenable to relatively simple techniques, the simultaneous control of both NO_x and CO has presented problems using generally accepted control techniques. The foregoing occurs since CO requires time and a relatively high temperature, typically of the order of 2500°F ., to oxidize such to carbon dioxide (CO_2). Temperatures in excess of 2800°F . have been found to be conducive to NO_x formation. These factors can be understood by referring to Figure 3 which is a graph of the NO_x versus combustibles, such as CO, and illustrates the "emissions window" in which burners are considered to be operating at acceptable emission levels.

To sustain clean, efficient combustion, a region of stable burning must be created. In the absence of such, flame extinction or "blow-out" will occur. Combustion efficiency and flame stability are closely interrelated, the "blow-out" condition representing the case of zero combustion efficiency. Flame stabilization can be achieved by the use of a flame holding device or bluff body in the air/gas

mixture stream. Typical flame stabilizing devices include metal screens, rods, and flame inserts. It has been found that these flame stabilizing devices also reduce NO_x emissions. Radiant fiber and ceramic surface burners have also been used for similar reasons. In the foregoing cases, the rods or surfaces provide a heat absorbing mechanism capable of re-radiating the absorbed heat to an absorbing surface beyond the flame region. By such means the flame temperature is reduced with concurrent reductions in NO_x formation. A key element in this approach is the ability of the radiant emitter surface to remove a substantial proportion of the heat generated, thereby controlling flame temperature. Experimental evidence of this phenomena shows an increase in NO_x emissions as the heat flux to the emitter is increased. This since, for a fixed emitter geometry, i.e., surface area, the amount of heat radiation from the reaction zone is essentially constant, thereby impairing its ability to control the reaction temperature at the higher heat flux rates. Surface burners change from radiant to a blue flame mode as the heat flux (BTU/hr ins²) is increased. In general, at heat fluxes in excess of 1000 BTU/hr ins², the more common surface burners "blow-out"; prior to this large quantities of CO are also produced.

Because of the foregoing, it has become desirable to develop a burner system which minimizes the production of NO_x and which produces low levels of CO. Referring again to Figure 3 what is required is operation inside the "emissions window". Furthermore, emissions should remain within the window throughout the firing range from low to high fire.

SUMMARY OF THE INVENTION

It is known that the use of excess air in pre-mixed burners reduces NO_x emissions since such excess air decreases the temperature of combustion. In accordance with the present invention, it has been found that increasing the velocity of the air/gas mixture also reduces NO_x emissions since "residence time" is decreased. Increasing the velocity of the air/gas mixture does, however, create a problem of flame "lift-off" from the burner. To prevent the occurrence of flame "lift-off" while minimizing NO_x production, flame stabilizing devices may be employed. The stabilizers may be constructed from any suitable configuration of heat resistant materials. Figures 4 through 6 and 8 through 10 show various types of pre-mix burners that can utilize the methodology of the present invention. Burners of the type shown have been operated with port face loadings in the range of 5,000-100,000 BTU/hr ins². Flame stabilization can

also be achieved by aerodynamic means, e.g., opposed jet recirculation, wake flow, etc., eliminating the need for mechanical stabilizers.

What was not recognized in the prior art was the contribution of "residence time" in the formation of NO_x. By increasing the velocity of the air/gas mixture, the "residence time" at the combustion reaction temperature is reduced. Port face loadings in the 5,000 - 100,000 BTU/hr ins² range represent a ten to twentyfold reduction in "residence" time as compared to prior art burners. It should be recognized that the foregoing port face loadings are based upon the total port face area and not the open or slot areas that form the air gas mixture passageways.

Experiments were conducted at the high heat flux rates using ribbon, ported ceramic, and porous ceramic burner types. Both ceramic rod and wire mesh flameholder types were also used. In all cases, the combustion emissions of both NO_x and CO were very low; Figure 11 depicts typical results obtained.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows the theoretical concentration of NO_x produced versus time and temperature as calculated using the Zeldovich chain reaction model.

Figure 2 is a graph of Air/Fuel Ratio versus Blow-Off Velocity for nozzle mix burners and premix burners.

Figure 3 is a graph of the Oxides of Nitrogen versus Combustibles, such as CO, and illustrates the "emissions window" in which burners are considered to be operating at acceptable emission levels.

Figure 4 is a cross-sectional view of one type of pre-mix burner utilizing external flame stabilization apparatus and which can be operated using the methodology of the present invention.

Figure 5 is a cross-sectional view of another type of pre-mix burner utilizing external flame stabilization apparatus and which can be operated using the methodology of the present invention.

Figure 6 is a cross-sectional view of still another type of pre-mix burner utilizing external flame stabilization apparatus and which can be operated using the methodology of the present invention.

Figure 7 is an enlarged partial cross-sectional view of the distributor plate illustrated in Figure 6 and illustrates the configuration of the ports therein.

Figure 8 is a cross-sectional view of one type of pre-mix burner utilizing internal flame stabilization apparatus and which can be operated using the methodology of the present invention.

Figure 9 is a cross-sectional view of another type of pre-mix burner utilizing internal flame stabilization apparatus and which can be operated using the methodology of the present invention.

Figure 10 is a cross-sectional view of still another type of pre-mix burner utilizing internal flame stabilization apparatus and which can be operated using the methodology of the present invention.

Figure 11 is a graph of NO_x Emissions versus Percent Excess Air.

DESCRIPTION OF THE PREFERRED EMBODIMENT

The production of NO_x is a function of combustion temperature and the time required to complete combustion. In addition to the previously mentioned prior art methods for reducing NO_x emissions, it is known that the use of excess air in the air/gas mixture also decreases the production of NO_x. The reduction in NO_x production in this case can be attributed to a decrease in the temperature of combustion as a result of the excess air. Alternatively, an increase in the velocity of the air/gas mixture can be utilized to reduce NO_x emissions. Such an increase in velocity can be achieved by reducing the size of the orifices through which the air/gas mixture flows or by increasing the port face loadings. By increasing the velocity of the air/gas mixture, the "residence time" associated with the formation of a flame is decreased, i.e., the combustion gases are in the reaction zone of the flame for a significantly shorter period of time which, in turn, reduces the production of NO_x. The velocity of the air/gas mixture can only be increased to a level where the flame begins to "lift-off" the burner. An increase in the velocity of the air/gas mixture beyond the foregoing level results in the flame being blown out. In order to increase the velocity of the air/gas mixture beyond the velocity where flame "lift-off" occurs, a flame stabilizing device must be utilized.

Referring again to the drawings, Figure 4 is a view of one of a number of burner units 10 which utilizes a flame stabilizing device and which can be operated using the methodology of the present invention to produce a very low level of NO_x emissions. The burner unit 10 includes a plenum 12 with a distribution plate 14 extending across its upper surface forming the outlet of the burner. The distribution plate 14 has a plurality of orifices or ports 16 passing therethrough. A flame arrester/distributor matrix 18 is positioned adjacent the upper surface of the distribution plate 14. Another embodiment of a burner unit which utilizes a flame stabilizing device and which can utilize the methodology of the present invention so as to produce a very low level of NO_x emissions is

burner unit 20 illustrated in Figure 5. Burner unit 20 includes a burner body 22 and a plurality of parallel flame arrester/distributor ribbons 24 adjacent its upper surface forming ports 26 therebetween. A still another embodiment of a burner unit which utilizes a flame stabilizing device and which can utilize the methodology of the present invention so as to produce a very low level of NO_x emissions is burner unit 30 illustrated in Figure 6. Burner unit 30 includes a ceramic tile distributor plate 32 having a plurality of ports 34 therein as shown in Figure 7. Each port 34 has a through portion 36 of substantially constant diameter or may incorporate a tapered portion 38 of increasing diameter from its junction with through portion 36 to the outer surface 40 of the distributor plate 32. The foregoing burner units are merely examples of some types of burners that can utilize the methodology of the present invention so as to produce very low levels of NO_x emissions. Many other types of burners can be utilized with similar results and there are no restrictions as to burner size, shape, porting configuration, method of fabrication, or materials utilized for same. Regardless of the type of burner utilized, the plenum or burner body is connected to an air-gas supply. In this manner, a combustible mixture of air and gas is supplied to the plenum or burner body from the air-gas supply. In any event, one or more flame stabilizing devices are positioned a short distance above the ports in the burner units utilized. The flame stabilizing devices may include one or more ceramic flame rods, wire mesh flame screens, or any combination thereof, in order to stabilize the flame above the ports provided in the burner utilized. It should be noted that in addition to stabilizing the flame above the ports, the flame stabilizing devices may also produce radiant heat which further serves to suppress NO_x formation.

Experimentally, flame screens formed from 0.092 in. Nichrome or Inconel wire have been used successfully with various types of burners. The optimum distance between the flame stabilizing means and the top of the burner to minimize the production of NO_x can be determined empirically or by experimentation.

Alternatively, if the burner has a single or a relatively small number of outlet ports, a bluff body 60 can be located within the outlet 62 of the burner, shown generally by the numeral 64, in Figure 8. The bluff body 60 can be formed from any of a variety of geometries, e.g., a weld cap having a generally semi-spherical configuration, or the like, which is held within the outlet 62 of the burner by means of set screws 66 which are threadably received through the bluff body 60 so that their ends contact the inner surface of the burner 64. Bluff body 60 is positioned within the

outlet 62 so that the flow of the air/gas mixture contacts the convex surface of same. In this manner, the bluff body 60 presents a contoured obstruction to the flow of the air/gas mixture. In Figure 8 a separate pilot (not shown) is utilized to ignite the air/gas mixture and the velocity of the air/gas mixture approaches the velocity at which the flame begins to "lift-off" the surface defining the outlet 62 of the burner 64. It should be noted that flow of the air/gas mixture impinges upon the upstream face of the bluff body 60, and then recirculates counter to the air/gas flow direction in a zone on the downstream side of the bluff body creating a region which supports combustion before passing outwardly therefrom to the outlet 62 of the burner 64.

Another burner structure which incorporates flame stabilization is shown in Figure 9 and includes a bluff body 70 attached to the end of a pilot tube 72. Here again, the bluff body 70 can be formed from any of a variety of geometries, e.g., a weld cap having a generally semi-spherical configuration, or the like. Alternatively, the pilot tube 72 and the bluff body 70 can be formed from a pipe and a reducing coupling. The pilot tube 72 and bluff body 70 are received within the outlet 74 of the burner, shown generally by the numeral 76, and are held within same by means of set screws 78 which are threadably received through the bluff body 70 so that their ends contact the inner surface of the burner 76. The pilot tube 72 and the bluff body 70 are positioned within the burner 76 so as to be substantially concentric therein. The air/gas mixture passes through a passageway 80 between the outer surface of the pilot tube 72 and the inner surface of burner 76 and the mixture impinges upon the upstream face of the bluff body 70, and then recirculates counter to the air/gas flow direction in a zone on the downstream side of the bluff body 70 creating a region which supports combustion. After ignition of the air/gas mixture by the pilot flame within the pilot tube 72, the resulting combustion gases pass to the outlet 74 of the burner 76. As in the burner structure illustrated in Figure 8, the velocity of the air/gas mixture approaches the velocity at which the flame begins to "lift-off" the surface forming the outlet 74 of the burner 76. It has been found that the foregoing bluff bodies in Figures 8 and 9 provide flame stabilization, permitting the velocity of the air/gas mixture to be increased beyond the velocity at which flame "lift-off" would occur if a flame stabilizing device had not been used. It has also been found that the use of such bluff bodies negates the need for a flame stabilizing device exterior to the outlet of the burner.

A still another burner structure which incorporates flame stabilization is shown in Figure 10 and includes a flameholder 90 attached to the end

of a pilot tube 92. The flameholder 90 can be cup-shaped and acts as a bluff body, as in the structure shown in Figures 8 and 9. The pilot tube 92 is positioned within a pipe 94 so as to be substantially concentric therein. The circumferential end 96 of pipe 94 abuts a refractory diffuser 98 having a tapered opening 100 therein. The diameter of the tapered opening 100 increases from the inner surface 102 of the refractory diffuser 98 to the outer surface 104 thereof. The inner diameter of pipe 94 is approximately the same as the diameter of the tapered opening 100 at the inner surface 102 of the refractory diffuser 98. The pipe 94 is aligned with the tapered opening 100 so that no discontinuities exist between the surface defining the inner diameter of the pipe 94 and the surface defining the tapered opening 100 in the refractory diffuser 98. A swirl vane assembly 106 is positioned adjacent the outlet 108 of the flameholder 90 and is interposed between the flameholder 90 and the surface defining the tapered opening 100 in the refractory diffuser 98. Air and fuel are provided through apertures 110 and 112, respectively, in the burner housing 114 and pass through a plurality of mixing venturis 116 into a chamber 118 before passing into pipe 94 through end 120 thereof. The air/gas mixture passes through a passageway 122 between the inner surface of the pipe 94 and the outer surface of the pilot tube 92 into a passageway 124 between the surface defining the tapered opening 100 in the refractory diffuser 98 and the outer surface of the flameholder 90. As the air/gas mixture passes through the swirl vane assembly 106, the mixture recirculates counter to the air/gas flow direction in a zone on the downstream side of the flameholder 90 creating a region which supports combustion. After ignition of the air/gas mixture by the pilot flame within the pilot tube 92, the resulting combustion gases pass outwardly therefrom to the outlet 126 of the burner. The velocity of the air/gas mixture approaches the velocity at which the flame begins to "lift-off" the surface forming the outlet 126 of the burner. As in the previous burner structures, the flameholder 90 permits the velocity of the air/gas mixture to be increased beyond the velocity at which flame "lift-off" would occur if a flameholder had not been used.

Regardless of whether a flame stabilizing device is utilized, it has been found that NO_x emissions can be held to acceptable levels by operating the burner unit with high velocity excess air to keep the combustion temperature slightly below the temperature at which a significant amount of NO_x is produced and to minimize the "residence time" associated with the formation of a flame. In the method of the present invention, a high velocity premixed air and gas stream in combination with

high heat flux rates, together with suitable proportions of excess air, has been shown to control the "residence time" and temperature thereby minimizing NO_x emissions. However, because of the high velocity of the excess air, flame stabilizing devices in the form of flame rods, flame screens or bluff bodies might be required to ensure that the flame does not "lift-off" the burner. The use of a flame stabilizing device increases the maximum flame extinction or "blow-out" velocity of the air-gas mixture. The device may also act as a radiator of heat thus keeping the resulting temperature from exceeding the temperature at which a significant amount of NO_x is produced. It should be noted, however, that flame stabilization can also be achieved by aerodynamic means, e.g., opposed jet recirculation, wake flows, etc., eliminating the need for a stabilizing device. It has been found with foregoing operating conditions that a very high heat flux of approximately 5,000-100,000 BTU/hr in.² can be achieved; the former heat flux of approximately 5,000 BTU/hr in.² being without the utilization of a flame stabilizing device, the latter heat flux of approximately 100,000 BTU/hr in.² being achieved with the utilization of a flame stabilizing device. Referring now to the graph shown in Figure 11, it is apparent that NO_x emissions decrease as the percent of excess air increases. If more than 20% excess air is utilized, NO_x emissions will be held within recently proposed standards. Thus, with the foregoing operating parameters, viz., 3000 degrees F. nominal operating temperature and high heat flux rates combined with suitable proportions of excess air, acceptable NO_x levels can be achieved. It has been further found with the foregoing operating parameters that as heat flux increases, the production of NO_x decreases if "residence time" is minimized. This was not the case with prior art burner systems wherein an increase in heat flux resulted in a commensurate increase in NO_x emissions. This latter benefit, i.e., a decrease of NO_x emissions with an increase in heat flux, has not been previously taught.

It has been found in oxygen enriched applications, which generally have higher flame temperature resulting in increased NO_x production, that an increase in the velocity of the air/gas mixture decreases "residence time" which, in turn, reduces NO_x production. Similarly, in applications where the air/gas mixture has been preheated, which typically results in a higher flame temperature, pre-heating increases the velocity of the air/gas mixture resulting in decreased "residence time" and thus, reduced NO_x production.

Another feature of the present invention is that the resulting production of NO_x and CO are within the "emissions window" shown in Figure 3. As previously stated, conventional burners typically

produce NO_x and CO in inverse proportions since time and temperature, both of which are conducive to NO_x formation, are required to reduce CO to CO₂. Test results using the methodology of the present invention, i.e., 20% and greater excess air at a high velocity, reveal that even though extremely low levels of NO_x are produced, approximately 20 ppmv, the production of CO is not excessive and is within the "emissions window". Thus, the methodology of the present invention minimizes the production of NO_x while producing low levels of CO.

Certain modifications and improvements will occur to those skilled in the art upon reading the foregoing. It should be understood that all such modifications and improvements have been deleted herein for the sake of conciseness and readability, but are properly within the scope of the following claims.

Claims

1. A method of operating a burner to reduce the NO_x emissions produced thereby comprising the steps of:
 - placing a flame stabilizing device adjacent the burner;
 - premixing air and gas in a manner such that excess air exists in the resulting mixture;
 - increasing the velocity of said air/gas mixture through the burner to decrease the time required for flame formation; and
 - igniting said air/gas mixture.
2. The method as defined in claim 1 wherein said flame stabilizing device is positioned adjacent the outlet of the burner.
3. The method as defined in claim 1 wherein said flame stabilizing device is positioned within the outlet of the burner.
4. The method as defined in claim 1 wherein said flame stabilizing device is positioned exteriorly of the outlet of the burner.
5. The method as defined in claim 1 wherein the velocity of said air/gas mixture is increased by reducing the size of the orifices through which said air/gas mixture passes within the burner.
6. The method as defined in claim 1 wherein the velocity of said air/gas mixture is increased by increasing the port face loading of the burner.

7. The method as defined in claim 1 wherein the velocity of said air/gas mixture approaches the velocity at which the flame begins to "lift-off" the outlet of the burner. 5
8. The method as defined in claim 1 wherein said flame stabilizing device is at least one flame rod. 10
9. The method as defined in claim 1 wherein said flame stabilizing device is a flame screen. 15
10. The method as defined in claim 1 wherein said flame stabilizing device is a combination of a flame screen and at least one flame rod. 20
11. The method as defined in claim 1 wherein said flame stabilizing device is a bluff body. 25
12. A method of operating a burner to reduce the NO_x emissions produced thereby comprising the steps of:
 premixing air and gas in a manner such that excess air exists in the resulting mixture;
 increasing the velocity of the air/gas mixture through the burner to decrease the time required for flame formation;
 igniting said air/gas mixture; and
 stabilizing the resulting flame by aerodynamic means. 30
13. The method as defined in claim 9 wherein said aerodynamic means comprises opposed jet recirculation. 35
14. The method as defined in claim 9 wherein said aerodynamic means comprises wake flows. 40

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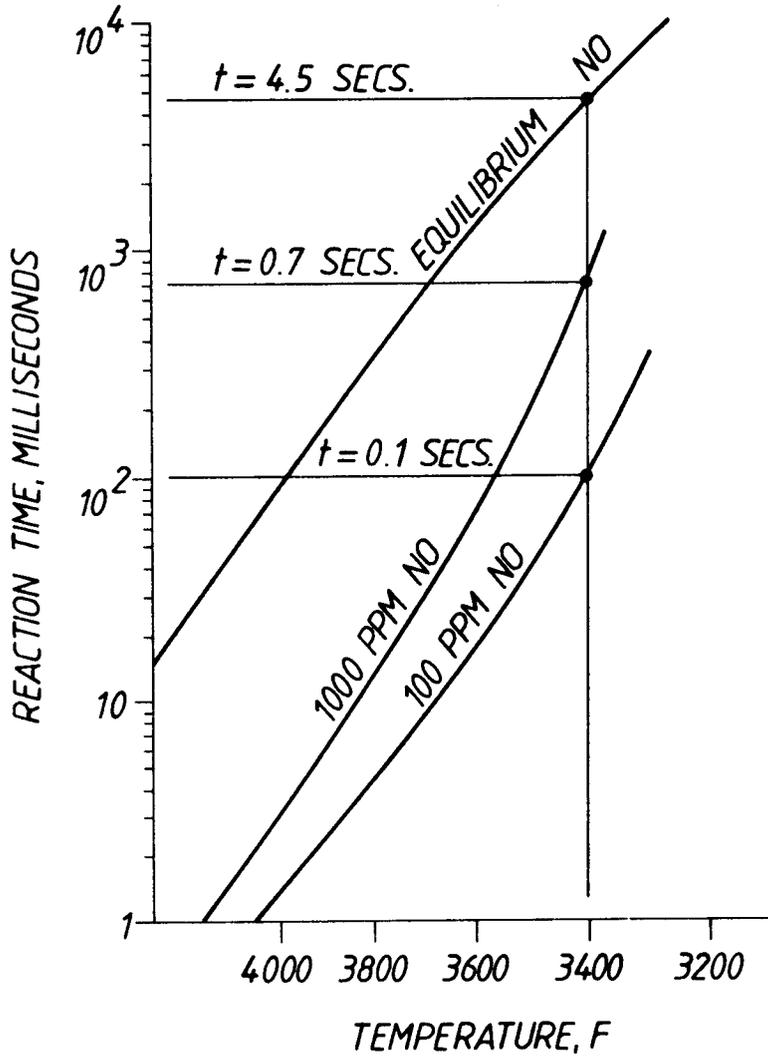


Fig.1.

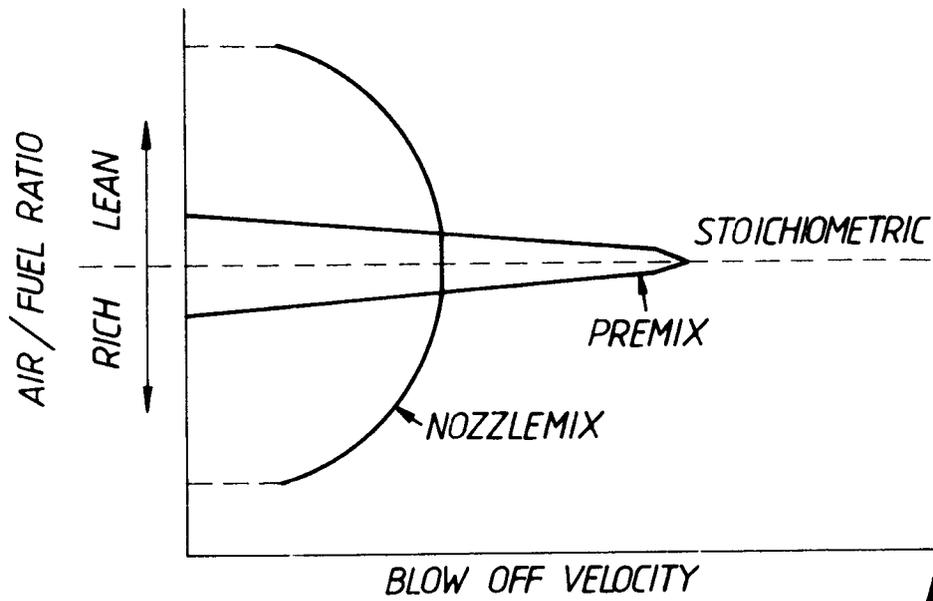


Fig.2.

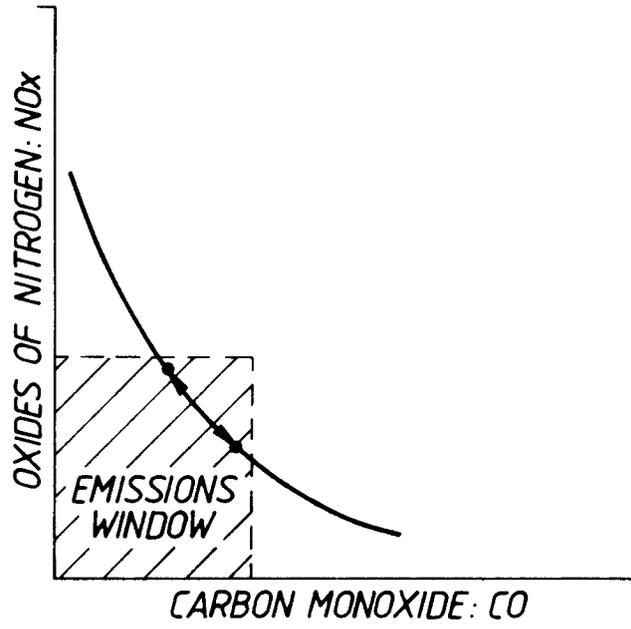


Fig.3.

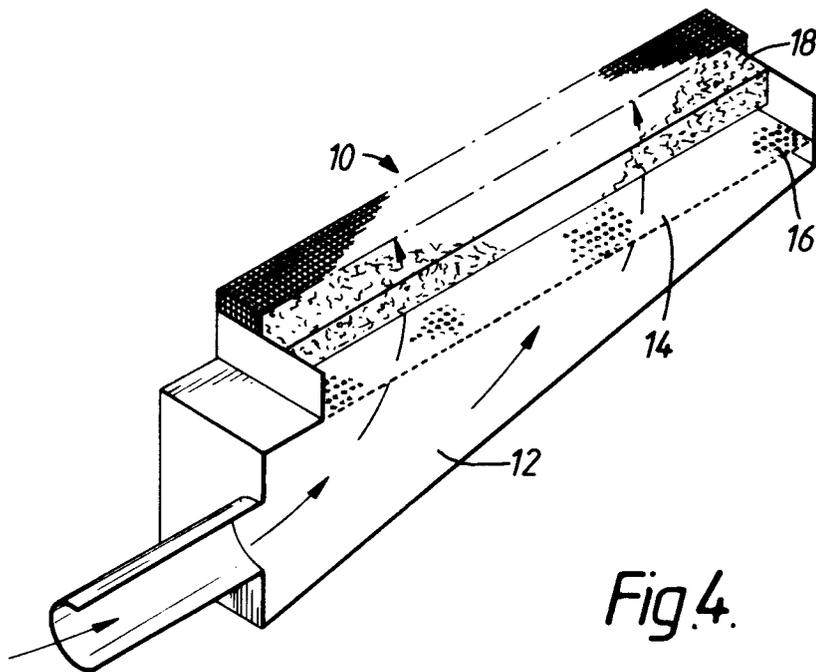


Fig.4.

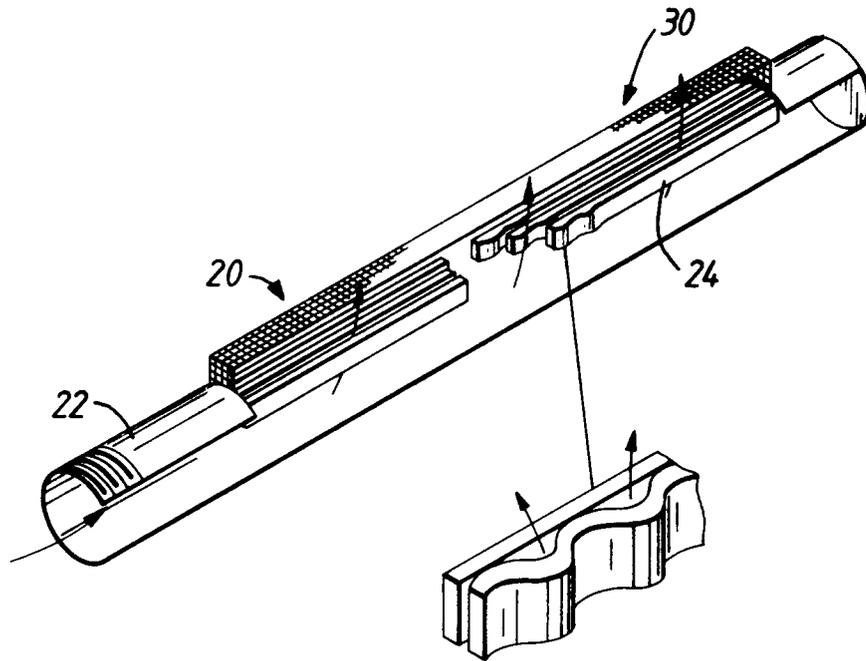


Fig. 5.

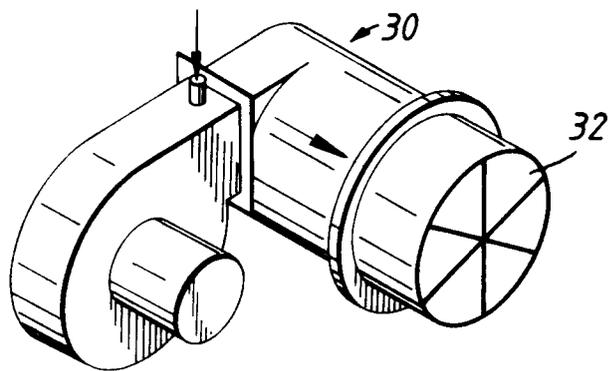


Fig. 6.

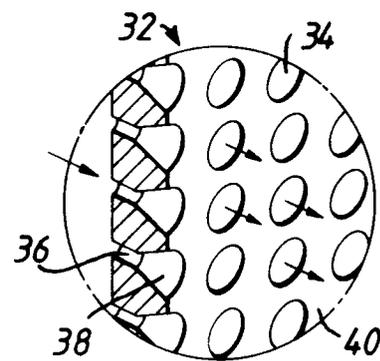


Fig. 7.

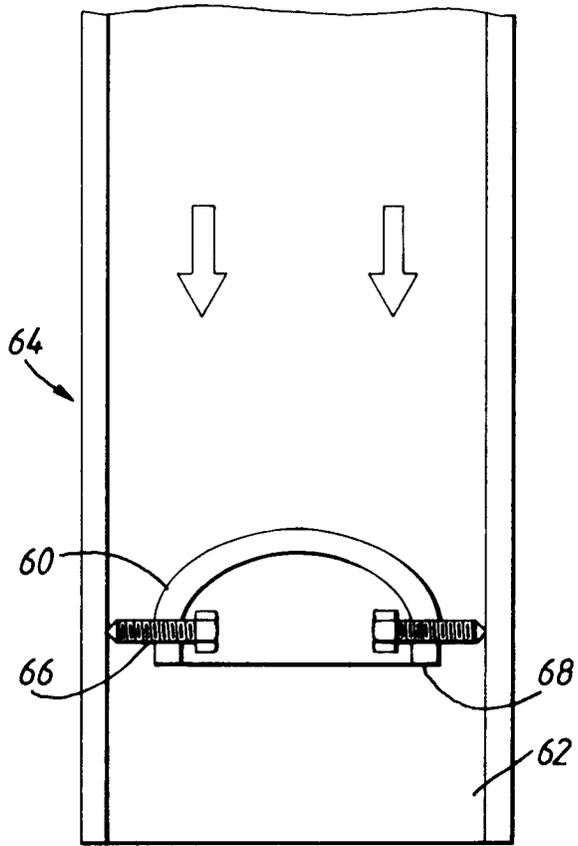


Fig. 8.

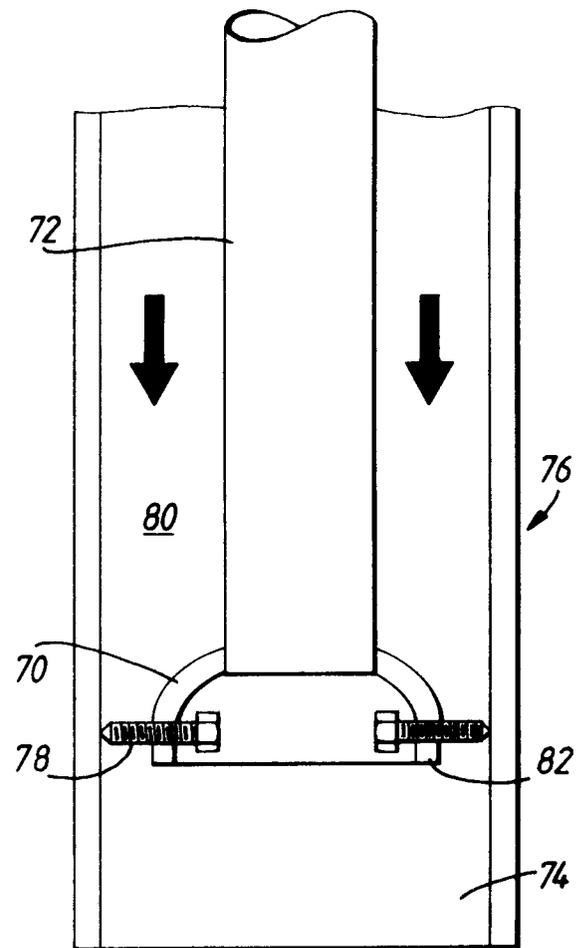


Fig. 9.

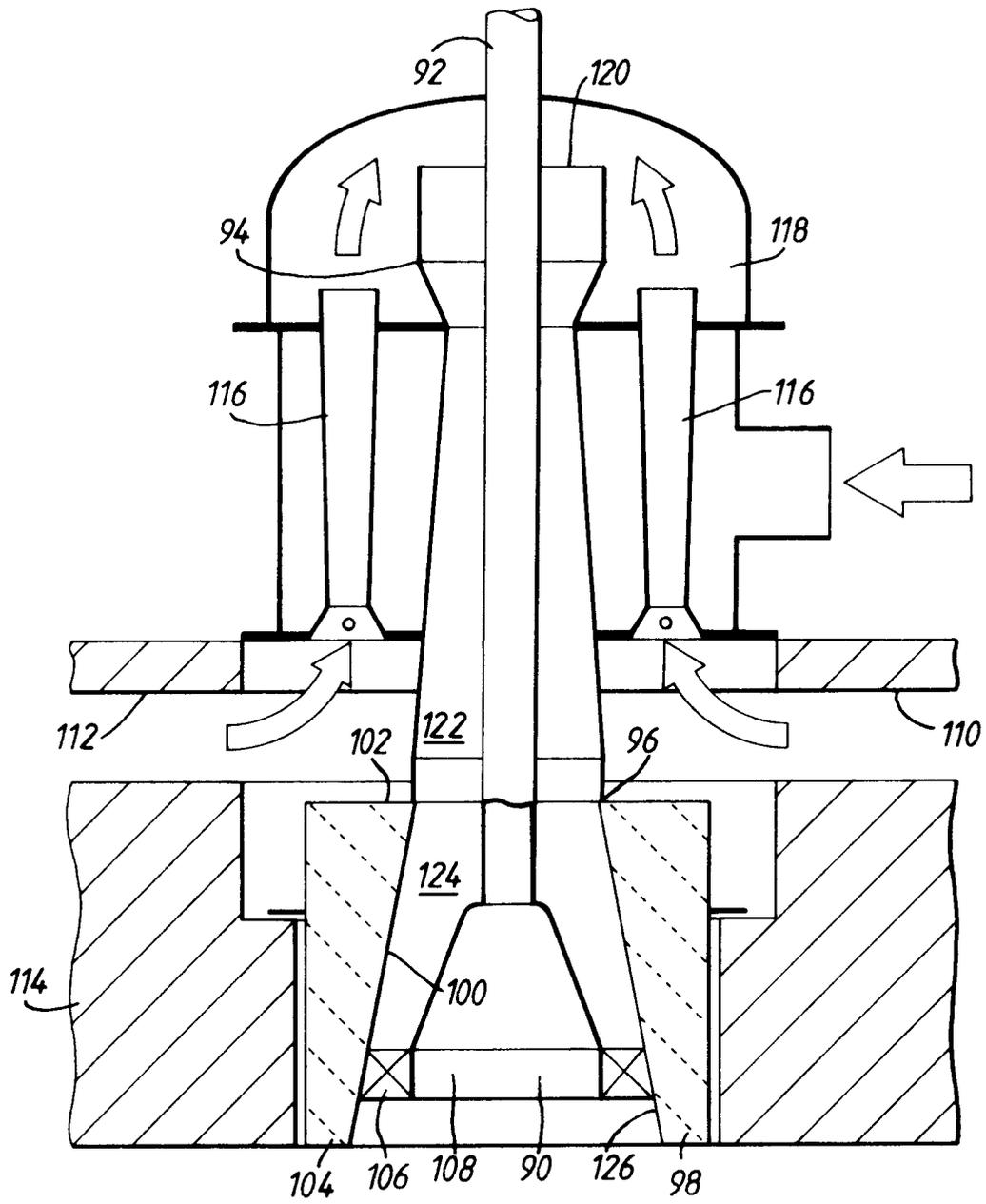


Fig.10.

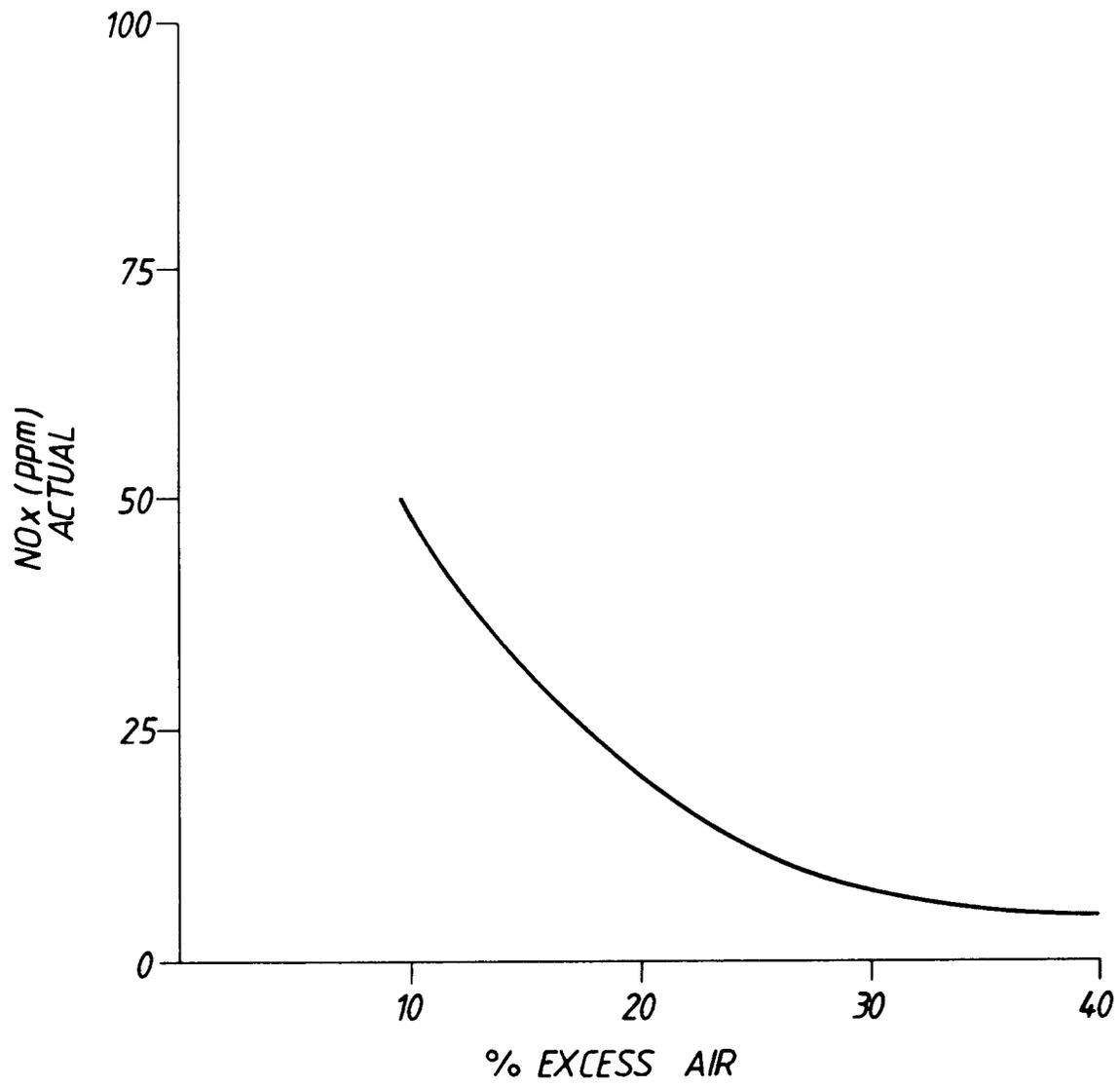


Fig.11.