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ABSTRACT

A gas-fired cyclonic combustor has been developed for relatively low-temperature direct-air heating applications that require ultra-low pollutant emissions. High-lean premixed combustion with a flame stabilizer is adopted to achieve ultra-low emissions and high turndown operation. On the basis of analytical studies and cold modeling, a 350-kW test combustor was designed and successfully tested.

Experimental results obtained using natural gas and ambient air demonstrated that the test combustor can operate steadily at high excess air up to 80% to 100% over a large turndown range up to 40:1. At design operating conditions, NO_x emissions as low as 0.6 vppm and CO and total hydrocarbon (THC) emissions below 3 vppm* were achieved. Over the full operating range, NO_x emissions from 0.3 to 1.0 vppm and CO and THC emissions below 4 vppm were demonstrated. In all tests, concentrations of NO_2 were less than 40% of the total NO_x emissions – lower than the level of NO_2 emissions from combustion processes required for good indoor air quality (0.5 vppm).

This paper presents the concept of high-lean premixed ultra-low-emission cyclonic combustion, design specifications for the combustion system, and the major experimental results, including flame stability, emissions, and turndown performance.

INTRODUCTION

Fuel-fired hot-air systems are widely used in a variety of industrial, commercial, and residential applications where relatively low-temperature hot air is needed for heating or drying. Basically, the two different approaches for heating air by a primary heat source provided from fuel combustion are 1) indirect and 2) direct. In indirect systems, the process air is not mixed with the products of combustion (POCs) but rather extracts the heat of combustion via a heat exchanger. In direct systems, the process air is mixed with POCs and then delivered to the heating or drying process. Therefore, almost 100% of the heat of fuel combustion is utilized for the process in direct-fired systems. In addition, direct-fired hot-air systems require the lowest capital and operating costs because expensive heat-exchange equipment is not required However, the disadvantage of direct-fired systems is that POCs, which contain varying amounts of nitrogen oxides (NO_x), carbon monoxide (CO), unburned total hydrocarbons (THC), and possibly particulate matters (PM), can "vitiate" the environment (for example, indoor and

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* Unless otherwise specified, all pollutant emission data in this paper are corrected to 15% O_2.

greenhouse atmospheres) or many products (barley malt, powdered milk, and baked meats, etc.). Therefore, in many applications, direct-fired air-heating systems have been replaced with more costly electric heating systems or less efficient and more complex indirect-fired systems to avoid contact of the POCs with the products.

One of the major applications for direct gas-fired hot-air systems is unvented space heating. Recent investigation by the U.S. EPA Clean Air Science Advisory Board has shown that concentrations of nitrogen dioxide (NO_2) in the 0.1 to 0.3 vppm (at 0% O_2) range in indoor air may cause adverse health effects. Therefore, indoor air with less than 0.1 vppm NO_2 is considered "good quality" air based on the Pollutant Standards Index (PSI) Range and Description category specified in the Code of Federal Regulation (CFR, 1989).[1] According to the American National Standard (ANS, 1983) for gas-fired room heaters,[2] this requires NO_2 emissions from a direct-fired burner to be no more than 1.75 vppm (at 0% O_2, or 0.5 vppm at 15% O_2). In a recent survey conducted by the Gas Research Institute (GRI), however, 98% of unvented gas-fired space heaters cannot provide good air quality.[3]

Another important application for direct gas-fired hot-air systems is drying and process heating. In the food-drying and heating industries, for example, the primary concern is the potential formation of nitrosamines and the pink color in foods from the relatively high levels of NO_x contained in the direct-heated air. Similar emissions concerned with "yellowing" problems in fibers and carpet-heating processes are also addressed.

On the basis of European regulations, American Gas Association (A.G.A.) recommendations, and feedback from the U.S. Industry, GRI has determined that the POCs from natural gas-fired combustors for direct air heating must not contain more than 0.5 vppm NO_x and 3 vppm CO. To date, no commercial gas-fired burners can achieve this target of emission levels. The gas industry in the United States is interested in developing advanced, economically feasible burners that produce ultra-clean products of combustion for direct use in space heating, process heating, and drying applications.

The Institute of Gas Technology (IGT) has teamed with Maxon Corp. to develop a gas-fired direct air heater based on the cyclonic combustion concept. This paper introduces this technology and presents the major experimental results obtained from a pilot-scale test combustor.

CONCEPT AND TECHNICAL APPROACH

NO_x Formation in Combustion Processes

Most nitrogen oxides (NO_x) are produced in the combustion process in two forms: nitric oxide (NO) and nitrogen dioxide (NO_2). NO is the initial oxidation stage in which the NO_x are formed. Because the process of oxidation of the atmospheric nitrogen is endothermic, the formation of NO takes place in high-temperature regions of the flame. The NO is then oxidized to NO_2 in the zone of considerable excess air.

It is commonly recognized that NO formation in combustion processes can be the result of three different mechanisms:

1. Thermal NO is produced by oxidation of molecular nitrogen.

2. Prompt NO is produced by high-speed reactions at the flame front.

3. Fuel NO is produced by oxidation of chemically-bound nitrogen contained in the fuel.

It is fairly well established that NO formation is strongly temperature-dependent, based on the Zeldovich mechanism.

The second mechanism has been invoked to explain the anomalously high concentration of NO that has been observed in flame fronts.[4] Because the reactions are endothermic and the activation energy and reaction heat are relatively low,[5] prompt NO formation can occur in relatively low-temperature flames and can still be accelerated by increasing flame-front temperatures.

The third mechanism is used to describe how fuel-bound nitrogen is converted to NO. Conversion of fuel-based nitrogen to NO also increases with increasing flame temperatures.

NO_x generated by the combustion of natural gas is primarily controlled by the Zeldovich mechanism. The rate of formation of thermal NO_x is highly temperature dependent.[6] Therefore, the technical direction for minimizing NO_x formation is to reduce temperature in the flame zone.

NO_x Reduction - Approach and Challenges

With an understanding of NO_x formation, the basic approaches toward lower NO_x emissions focus on reducing the concentration of free oxygen, residence time, and combustion temperature, including eliminating the "hot spots" in the combustion zone. The various proven practical combustion technologies for reducing NO_x formation include high excess air combustion, homogeneous combustion, staged firing, recirculation of combustion products, cooling of the combustion zone, and heat removal from the flame. However, the only approach that has reduced NO_x emissions to the levels of a few vppm is premixed gas combustion.

For most kinds of space and process heating applications for which ultra-low-combustion emissions are targeted but high combustion temperatures are not required, the favorable approach is high excess air premixed combustion because of its simple structure and operation and, thereby, low cost. Consistent reduction of NO_x emissions with an increase in excess air has been proven experimentally in many gas-fired test combustors.[7-12] The data show a clear trend that NO_x could be reduced to a level less than 1 vppm by increasing excess air greater than 80%. However, problems with combustion stability, especially at low load operation, can result. Moreover, any attempt to reduce NO_x by lowering combustion temperatures and minimizing the residence time may lead to an increase in CO and THC. Therefore, an advanced combustor to achieve ultra-low emissions for all combustion pollutants (NO_x, CO, and THC) should apply the following techniques:

- Premixed fuel/air combustion
- High excess air operation
- Excellent flame stabilization
- Intensive mixing in the combustor to minimize CO and THC formation.

For the applications of these techniques, the cyclonic combustion concept has been adopted at IGT as the ideal candidate.

Cyclonic Combustion

A conceptual cyclonic combustor is shown in Figure 1. Through the evenly spaced tangential nozzles, a premixed gas/air mixture is injected into the combustion chamber at a

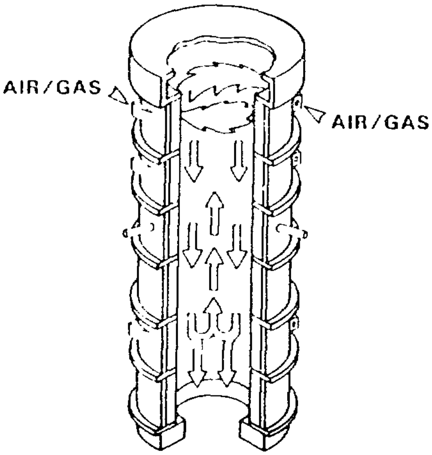

Figure 1. CONCEPTUAL FLOW PATTERN
IN A CYCLONIC COMBUSTOR

relatively high velocity, creating intensive cyclonic motion. Because the swirl intensity is usually much higher than that achieved by other types of swirlers (for example, axial or radial swirlers), intensive turbulent mixing and substantial internal combustion products recirculation (ICPR) that enhance flame stabilization as well as combustion completion are obtained. The intensive swirl and the ICPR can also improve the uniformity of temperature and gas composition in the chamber. As a result, high peak flame temperatures and localized pockets of high O_2 availability are minimized, thereby reducing NO_x formation. The swirl flow and ICPR are further enhanced by placing an orifice of appropriate size at a specific distance from the nozzles. Moreover, by appropriately positioning the tangential nozzles and controlling the velocities of nozzle injection, the flame established from each nozzle can be enhanced by each other. It is possible, therefore, to operate a premixed cyclonic combustor beyond the lean limit of flammability with sufficient intensity of combustion reaction to minimize the formation of all combustion pollutants.

Different types of cyclonic combustors based on this similar concept have been developed. For example, Syred's cyclone combustor has 14 tangential inlets arranged in two rows of seven for flame stabilization.[9] As low as 1-vppm NO_x emissions were demonstrated from this multi-inlet cyclonic combustor. The cyclonic combustor developed at IGT has only two to four tangential nozzles. Earlier tests at IGT had shown that NO_x emissions as low as 1 to 2 vppm were achieved in a single-stage cyclonic combustor.[8]

Further reduction of NO_x formation requires higher excess air operation. A flame stabilizer, as the first-stage combustor, was adopted to enhance flame stability of the higher lean premixed flame in the main combustor. Figure 2 shows a conceptual design of the two-stage cyclonic combustor. Both combustors are operated in a lean premixed combustion mode, while a less lean operation is desired in the flame stabilizer in order to provide "hotter" combustion gases for enhancing flame stability in the main combustor, which is operated at leaner conditions.

Setup

A 350-kW firing capacity test combustor was designed, fabricated, and tested. The combustor consists of a smaller cyclonic chamber as the flame stabilizer and a larger chamber as the main combustor. The combustion chambers are fully lined with refractory to provide a near-adiabatic environment for flame stabilization at very lean conditions. An orifice is installed

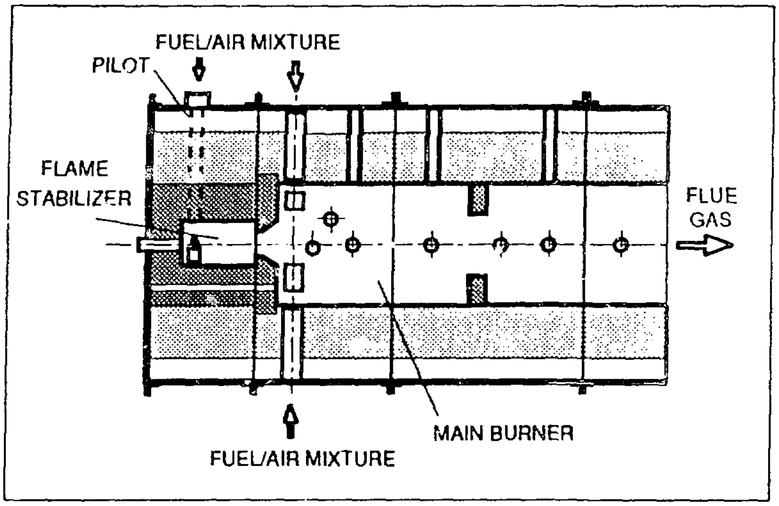

Figure 2. IGT/MAXON GAS-FIRED ULTRA-LOW-EMISSION TEST BURNER

at the exit of each combustion chamber for further enhancement of the internal combustion product recirculation. A configuration of the flame stabilizer, including the length/diameter ratio of the chamber and the size and shape of the exit orifice, was determined from cold modeling results; the location and size of the main combustor exit orifice remain variable in order to permit changes in the main combustor configuration.

Two tangential nozzles are employed for the flame stabilizer and four for the main combustor. Because the swirl flow and ICPR are driven by tangential injection from the nozzles, the injection velocity is an essential parameter for governing fluid dynamics in the cyclonic chamber. To enable optimized control of the nozzle velocity at different operating conditions, especially at turndown operation, all tangential nozzles are specially designed to allow a smooth adjustment of the cross-sectional area of the nozzle outlet while the combustor is operating.

A flow diagram of the test system is shown in Figure 3. Combustion air and natural gas are premixed individually for each stage of the combustor. Flow rates of air and fuel are also metered and controlled individually. The flow rate of the premixed fuel/air mixture for each nozzle can also be adjusted for flow balance control.

The test combustor is started up by a sequence start-up system that automatically controls system purge, ignition of a pilot by an electric spark, and fuel supply to each combustor. An interlock system is linked with the flame sensor monitoring the flame in the flame stabilizer for safety protection. Another flame sensor is installed on the main combustor. Signals from this sensor are acquired by the computer for monitoring flame stability and guiding combustion control in the main combustor.

Data Collection

The combustion rate and the ratio of air/fuel were measured individually for each stage. Exhaust-gas temperature and composition, inner wall temperature and pressure in the combustion chamber, and the static pressure at each nozzle were also measured for evaluation of the test combustor performance. The major data were collected by a computer data acquisition and reduction system, shown in Figure 3.

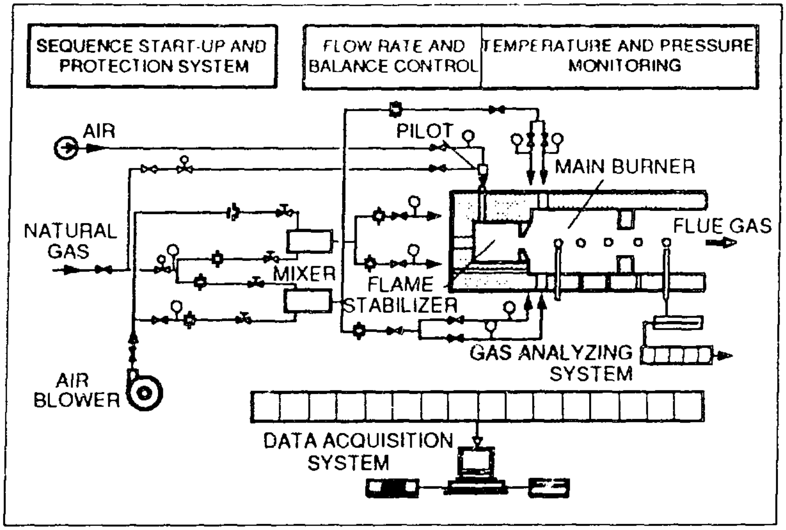

Figure 3. TEST SYSTEM OF THE ULTRA-LOW-EMISSION COMBUSTOR

Because measurement protocol for combustion emissions is not standardized and the emissions being measured in the current studies are ultra-low, sampling and analysis of combustion gases were carried out very carefully.

A water-cooled probe was used to sample the combustion products. The probe at the cold end was equipped with a section of externally heated stainless steel tubing to maintain a sample temperature of about 190°F so that moisture would not condense. The warm sample was passed through a millipore filter to remove any solid particles and a Permapure dryer to remove moisture. The dried sample was supplied to oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxide (NO and NO_x), and total hydrocarbon (THC) analyzers through Teflon tubing.

To ensure the accuracy of the measured emissions at ultra-low levels, all instruments were selected with appropriate operating ranges and calibrated before and after each test. The CO analyzer with a range of 0 to 50 vppm was calibrated by a 4.1-vppm span gas. The hydrocarbon analyzer with a range of 0 to 100 vppm was selected and calibrated by a 4.9-vppm span gas. The NO/NO_x analyzer was ranged from 0 to 1 vppm and 0 to 10 vppm, respectively, and calibrated by a 3.3-vppm span gas. Because the NO_x formation during combustion is comparable to that in ambient air, the NO_x concentration in the combustion air was monitored before and after each test. The NO_x content of combustion air was found to be from 0.08 to 0.25 vppm. Therefore, all NO_x emission data have been corrected to a net increment through the combustion process.

A suction pyrometer was used to measure gas temperature in the main combustor for evaluation of flame stability, as well as temperature uniformity.

The sophisticated design and test system are for the purpose of extensive evaluation studies. A practical unit will be simplified significantly based on the test results.

EXPERIMENTAL RESULTS

Experimental studies were conducted at different operating conditions and for five combustor configurations. The purpose of the parametric study was to evaluate the technical approach adopted for achieving ultra-low-combustion emissions at a high turndown ratio and to explore the effects of the various parameters on burner performance for optimal design.

Flame-Stabilization Enhancement by the Stabilizer

One of the major technical approaches for achieving high excess air operation is the use of the flame stabilizer. By inducing hotter combustion products from the stabilizer into the ignition zone of the main combustor, main flame stabilization can be enhanced. As a result, the main combustor can be operated at higher excess air to further reduce NO_x formation.

This concept has been proven experimentally. Figure 4 shows an increase in the maximum excess air in the main combustor with stabilizer operation and a corresponding reduction of NO_x emissions when the test burner was operated at high load. For example, the maximum excess air was increased from 65% to 73% at a 470-kW firing rate, and NO_x emissions were reduced by 40% from 1.6 to 1.0 vppm. However, when the burner was operated at low load, the use of the flame stabilizer did not reduce overall NO_x emissions but even resulted in a slight increase in NO_x, as shown in Figure 4, because the flame stabilizer made a larger contribution to overall NO_x formation. For the best results, the flame stabilizer should be applied for main flame stabilization at a relatively high load as well as for high turndown operation at low load.

Figure 5 shows NO_x produced in the stabilizer operating at different ratios of firing rates to that of the main combustor, as well as NO_x that contributed to the overall emissions, at a total firing rate of 300 kW. NO_x emissions from the stabilizer were reduced to as low as 0.9 vppm at a 44-kW firing rate. However, NO_x that contributed to the overall emissions generally increased with the firing rate in the stabilizer. On the other hand, the higher firing rate in the stabilizer is beneficial for enhanced flame stabilization in the main combustor, particularly at higher load operation. Therefore, low-firing-rate operation of the stabilizer will not make a positive contribution for overall NO_x reduction at both low and high load operation of the main combustor. An appropriate operating range for the stabilizer is between 8% and 15% of the overall firing rate, based on lower NO_x formation in the stabilizer as well as higher capability for flame stabilization, as shown in Figure 5. Within this firing-rate range, the NO_x formation for overall emissions is almost constant (0.12 vppm). As a result, a portion of NO_x formed in the stabilizer was reduced to a level of 20% in the overall NO_x emissions. A further increase in the firing rate of the stabilizer will dramatically increase the overall NO_x emissions.

Effect of Main Nozzle Velocity

As discussed earlier, nozzle velocity is an essential parameter for combustion control and performance. The effect of the main nozzle velocity on combustion emissions was studied for different burner configurations. It was found that, within a practical range of the main nozzle velocity, from 24 to 76 m/s, the effects of the nozzle velocity on both NO_x and CO emissions are less than 30%. Figure 6 presents the results obtained for a typical burner configuration.

In general, NO_x and CO emissions abated with an increase in nozzle velocity because flue-gas recirculation and mixing in the combustor are intensified at a higher swirl intensity. However, at a higher nozzle velocity, CO emissions, especially in the region near the wall, are increased because this portion of the reactant flow will have less residence time in the chamber due to the deterioration of uniformity of the cyclonic flow field when the swirl intensity is too high. This principle was explored using the results of residence-time distribution

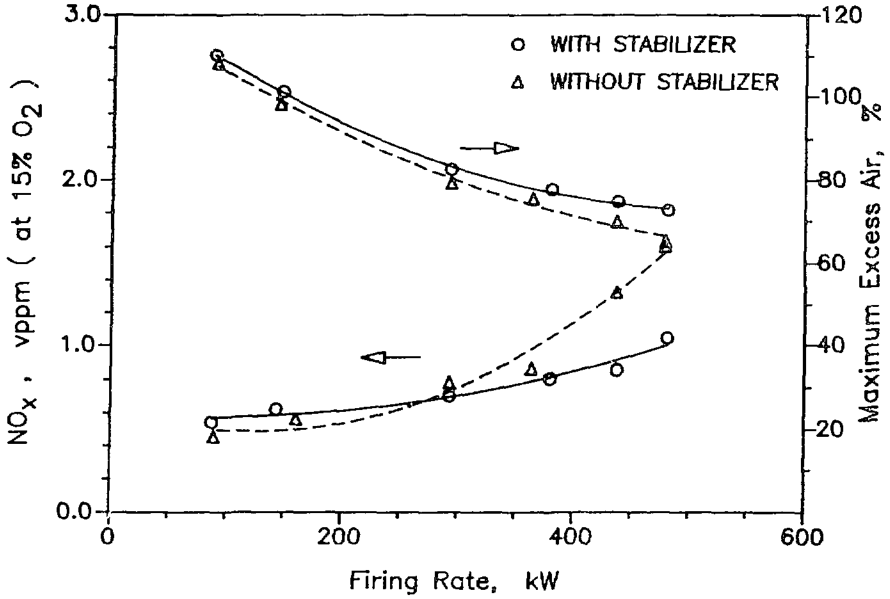

Figure 4. FLAME STABILIZATION ENHANCEMENT BY THE STABILIZER

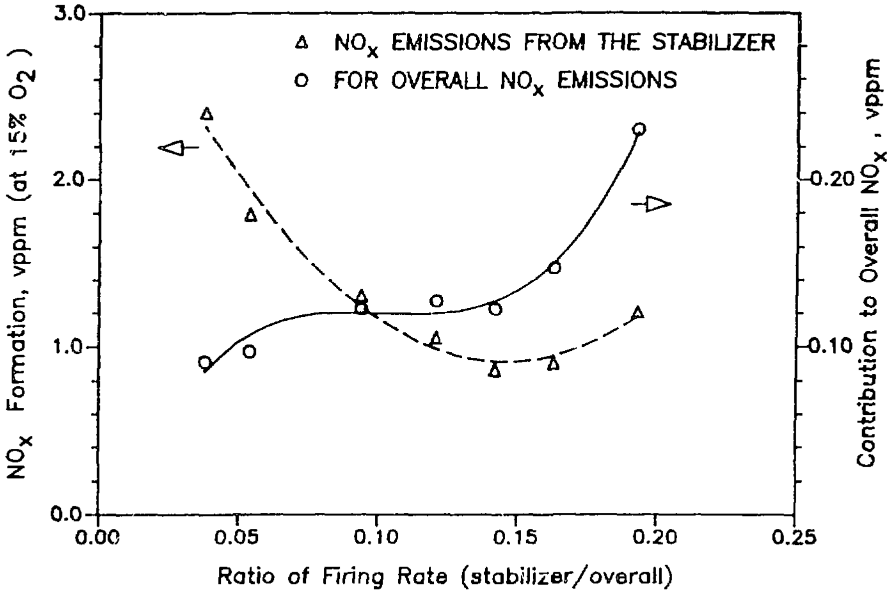

Figure 5. NO_x FORMATION FROM THE FLAME STABILIZER

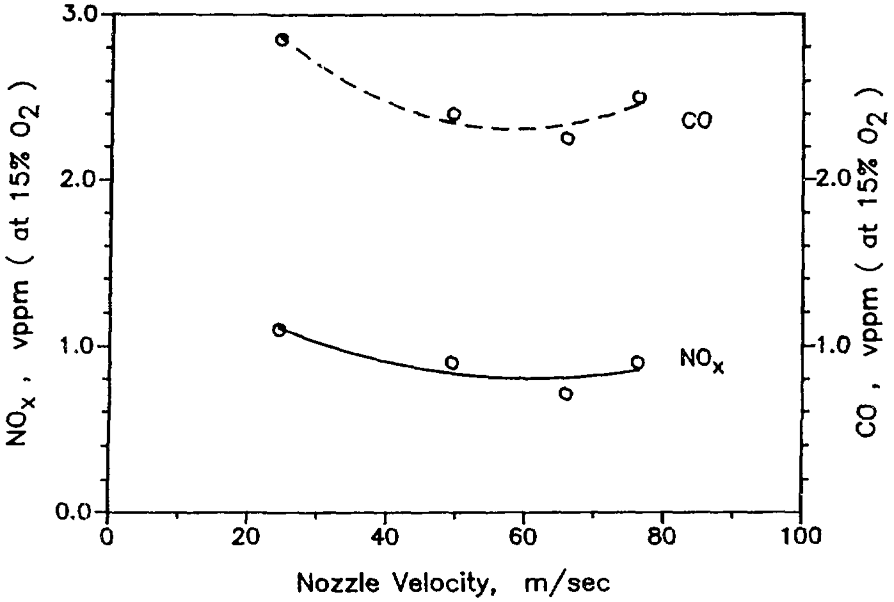

Figure 6. EFFECT OF NOZZLE VELOCITY ON EMISSIONS

measurements that were performed in the cold model. Therefore, the optimal main nozzle velocity can be recommended to be 50 to 60 m/s for this typical burner configuration.

When controlling the nozzle velocity within the optimized range, excellent performance of the test combustor was accomplished.

Effect of Excess Air

It is obvious that NO_x emissions are reduced with an increase in excess air at a given firing rate because it lowers the combustion temperature. In contrast, CO emissions increase with excess air because of the decrease in both combustion temperature and residence time. Figure 7 shows NO, NO_x, and CO emissions at different excess air at a 322-kW firing rate. It is seen that NO_x was reduced from 2.2 to 0.6 vppm and CO was increased from 1.6 to 2.8 vppm as excess air was increased from 57% to 80%. Correspondingly, the combustion temperature was decreased from 2460° to 2250°F. The NO and NO_x data also show that most of the NO_x emissions (70% to 90%) were contributed by NO. The NO and NO_x values were directly measured by the chemiluminescent analyzer, NO_2 values were determined only by difference; results show a range of 0.1 to 0.3 vppm for the test conditions employed. Therefore, the data presented in Figure 7 demonstrate that ultra-low emissions have been achieved.

The maximum excess air is limited for flame stabilization. At a lower load operation, the maximum excess air can be increased as high as 110%. The combustion temperature is correspondingly decreased to 2000°F, and NO_x emissions can be reduced to as low as 0.3 vppm, as shown in Figure 4.

Effect of Firing Rate (Turndown)

Turndown tests were conducted for all five configurations. At each level of the firing rate, excess air was gradually increased to reduce NO_x formation until an unstable flame appeared. The overall firing rates were varied from 12 to 500 kW with the main burner operation. The flame stabilizer was operated alone at very low overall firing rates ranging from

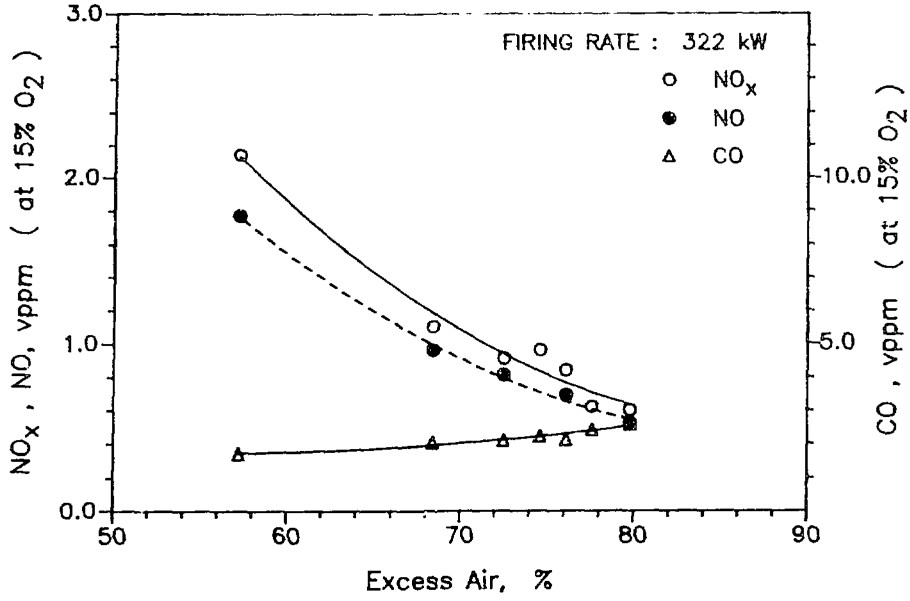

Figure 7. EFFECT OF EXCESS AIR ON EMISSIONS

12 to 60 kW. Then the main burner was started up at 60 kW to replace the flame stabilizer until it reached a firing rate of about 240 kW. The flame stabilizer was operating at 18 to 41 kW when the main burner was firing above 240 kW. Thus, an overall turndown as high as 40:1 was achieved by combined operation of the main burner (with 8:1 turndown) and the flame stabilizer (with 5:1 turndown). The maximum firing rate of the present test burner was limited by emission requirements, whereas the minimum firing rates for both the main burner and the stabilizer were restricted by the adjusting limits of the variable-discharge nozzle as well as the control devices (valves and flow-rate orifices).

Figure 8 presents test results of NO, NO_x, and CO emissions versus firing rate for a typical configuration. When the main burner was operated within an overall firing rate of 60 to 500 kW, NO_x emissions constantly increased from 0.3 to 1.0 vppm, with most of the contribution from NO. This occurred because the combustion temperature increased with increasing firing rate as a result of the decrease in the maximum excess air for flame stabilization as the firing rate was increased. It was found that the maximum excess air was decreased from 110% to 67% with an increase in the firing rate from 60 to 500 kW because flame stabilization at high excess air operation deteriorated when the axial velocity of the reactant flow increased. At very low load, NO_x emissions increased slightly because the flame stabilizer was operated alone. CO emissions from the combustor increased constantly from 1 to 3.6 vppm with increasing firing rate because of a corresponding decrease in residence time of the reactant flow in the combustor. Again, NO_2 emissions determined by the difference between NO_x and NO values were very low (0.1 to 0.4 vppm) over the full range of firing rates.

Test data have demonstrated that the test burner can operate stably at 40:1 turndown with NO_x emissions from 0.3 to 1 vppm and CO emissions from 1 to 3.6 vppm. In all tests, NO_2 was less than 40% of overall NO_x.

Effect of Main Burner Configuration

The major features of the combustor configuration are diameter and location of the exit orifice. The size of the orifice has a significant effect on the ICPR and residence-time

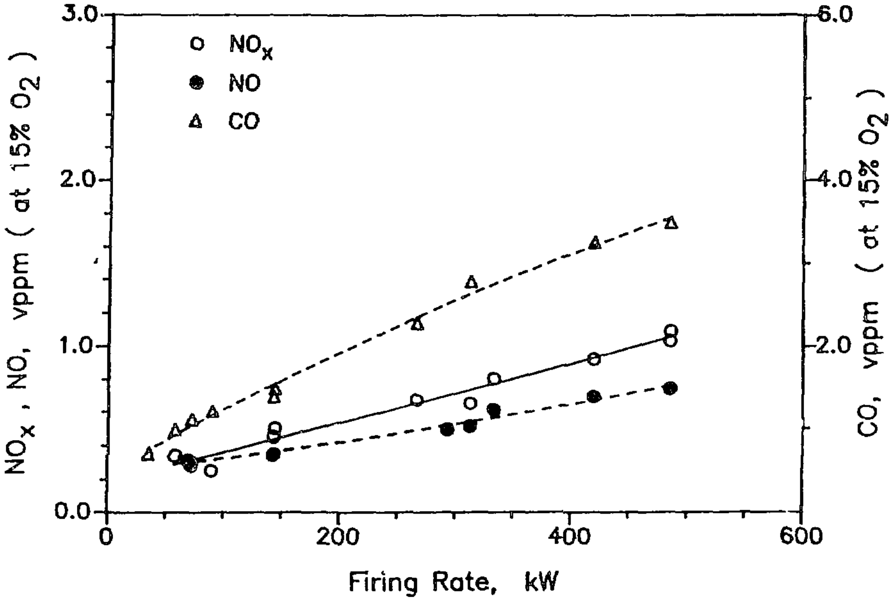

Figure 8. EFFECT OF FIRING RATE ON EMISSIONS

distribution of the reactant flow in the combustion chamber. The location of the orifice directly determines the length of the combustion chamber and also brings flow recirculation into effect.

Three different orifice sizes were tested. The ratios of the orifice diameters relative to that of the basic configuration were 0.82, 1.0, and 1.14. Because CO emissions are not critical to the present evaluation, only NO_x emissions are presented for comparison between different configurations. Figure 9 presents NO_x emissions obtained for different orifice sizes at different firing rates. It is obvious that the middle orifice size had the best performance in NO_x reduction. An orifice that is too large cannot produce strong flow recirculation and mixing, but an orifice that is too small cannot produce strong flow recirculation either because the diameter of the recirculation zone is reduced. Furthermore, it would result in an increase in CO emissions because a portion of the reactant flow would have less residence time in the combustor.

The effect of orifice location on NO_x formation at different excess air operation is shown in Figure 10. The ratios of distance from the orifices to the nozzles were 0.9, 1.09, and 1.15. Test results have demonstrated that the location of the exit orifice has no significant effect on NO_x formation at relatively low excess air but a considerable effect at high excess air operation.

Through the extensive parametric studies conducted at different combustor configurations and operating conditions, the optimized design of the ultra-low-emissions combustor can be specified for a commercial prototype.

TECHNICAL EVALUATION

A further technical evaluation of the present test combustor was conducted by comparing its performance to the existing commercial burners as well as a research prototype applied in direct-fired air heating.

Based on available technical information, the best performing commercial gas-fired combustor applied in direct air heating is the "CXA" gas burner developed by Urquhart Engineering Company, Ltd., in the U.K.[7,10] The major design features of this burner include

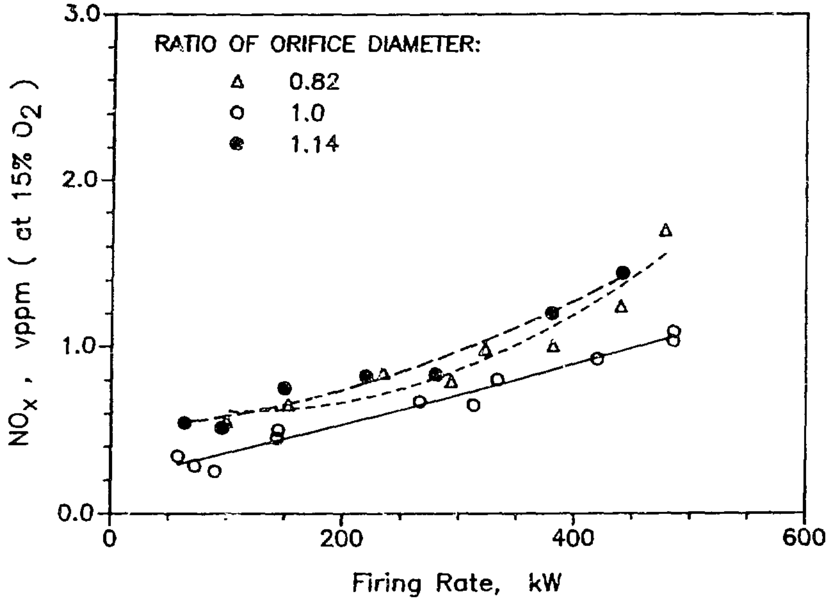

Figure 9. EFFECT OF ORIFICE DIAMETER ON NO_x EMISSIONS

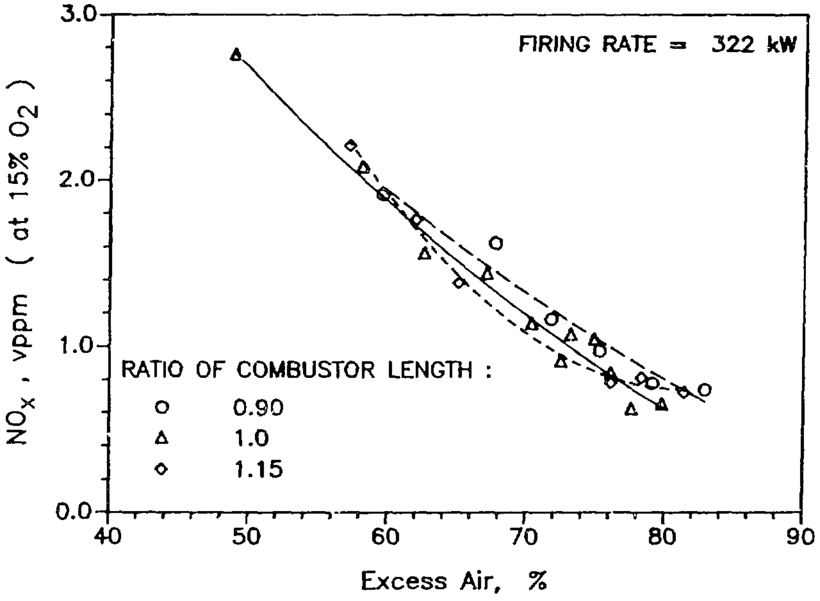

Figure 10. EFFECT OF ORIFICE LOCATION ON NO_x EMISSIONS

multi-venturi gas/air mixers, flame stabilizers, and a refractory-lined firetube to enhance flame stability at high excess air operation and ensure completeness of combustion before quenching of the combustion products by the air to be heated. The measured NO_x level from a test CXA burner was 1 to 1.6 vppm. The CO was only detectable at low firing conditions and fluctuated considerably over the 6 to 40 vppm range at the highest excess air ratio.[10] By using two parallel venturi sections, each of which has a turndown not exceeding 4.5:1, a two-stage configured burner can achieve an overall turndown ratio of 9:1. The CXA burner is commercialized and widely used in Europe and Australia.

Comparisons of NO_x and CO emissions between the CXA burner and the present cyclonic combustor operating at different firing loads are presented in Figures 11 and 12. NO_x emissions from the test CXA burner were decreased from 1 to 0.6 vppm with the load increasing from 12% to 95%, as shown in Figure 11. However, the test cyclonic combustor can operate at 40:1 turndown with NO_x emissions from 0.3 to 1 vppm.

The CO emissions comparison, as shown in Figure 12, has demonstrated that the CXA burner can only operate at a very small range in order to control CO emissions of less than 4 vppm. At very low (below 25% of full load) and high loads (above 90% of full load), CO emissions from the test CXA burner increases dramatically. In contrast, CO emissions from the test cyclonic combustor can be controlled below 4 vppm with 40:1 turndown operation.

Also, it should be noted that in order to achieve 9:1 turndown, the CXA burner must be composed of a two-stage combustor, resulting in the reduction of combustion intensity to one-half.

Therefore, the test cyclonic combustor has demonstrated better performance compared to the CXA burner, particularly in a much larger operating range with steady ultra-low emissions.

The levels of all emissions produced by this combustor is lower than the requirement for direct-fired air heaters, according to EPA, CFR, ANS, and GRI. A comparison of combustion performance from various direct gas-fired air heaters shows that the present cyclonic combustor demonstrated the lowest combustion emissions (NO_x, NO_2, and CO) and the highest turndown ratio. The Alzeta prototype space heater equipped with a Pyrocore, radiant burner outperforms other infrared and blue-flame burners with respect to most emission products and compares favorably with the Japanese fan heater. However, the IGT/Maxon test cyclonic combustor has demonstrated much lower amounts of combustion emissions than all burners listed in Table 1.[3] Moreover, these low combustion emissions were obtained over 40:1 turndown operation (8:1 for a single-stage operation alone), which is up to ten times greater than that for the other burners.

It must be noted that, because a chemiluminescent analyzer is used currently to measure NO and NO_x directly, NO_2 values are determined by difference. Consequently, some workers in this field question the absolute values of the NO_2 data reported in the vast majority of studies.[13] This suggests that there is a need to develop and validate a scientifically based standardized NO_2 measurement protocol. However, this suggested uncertainty does not cast doubt on the ultra-low-emission performance achieved in the test combustor because the maximum NO_2 emissions in all tests were below 0.5 vppm, which is lower than the target for good indoor air quality.

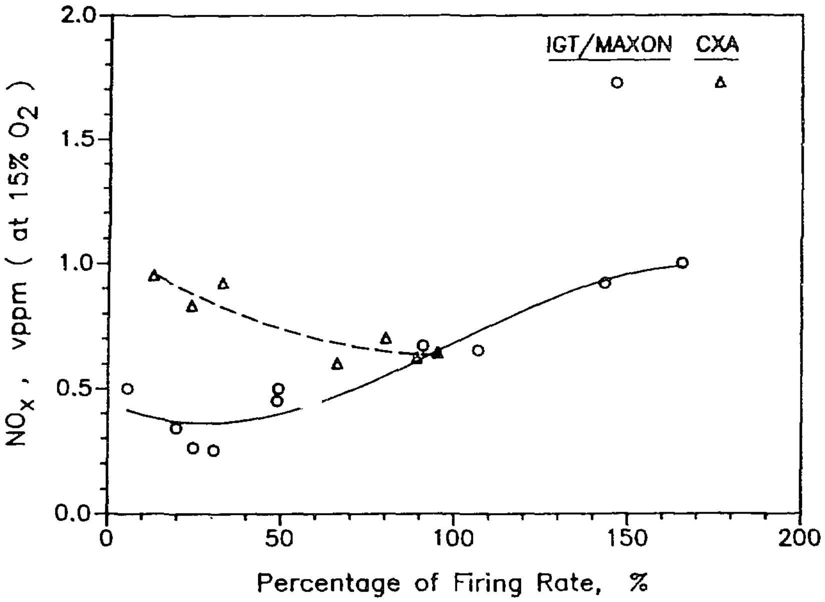

Figure 11. A COMPARISON OF NO_x EMISSIONS WITH THE 'CXA' BURNER

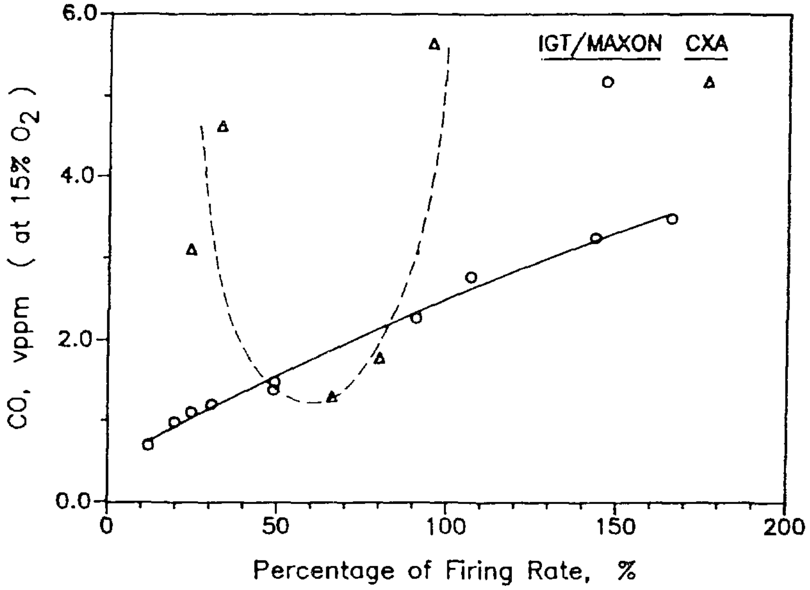

Figure 12. A COMPARISON OF CO EMISSIONS WITH THE 'CXA' BURNER

Table 1. COMPARISON OF EMISSIONS FROM VARIOUS GAS-FIRED COMBUSTORS FOR DIRECT SPACE HEATERS

Source	Emissions, µg/kJ (vppm, at 15% O_2)		
	NO	NO_2	CO
Convective (Blue Flame)	9.9 - 44.3 (6.1 - 27.1)	7.7 - 10.7 (4.7 - 6.5)	3.4 - 16.7 (2.1 - 10.2)
Infrared	1.7 - 0 (1.0)	1.7 - 5.2 (1.0 - 3.2)	4.7 - 87.3 (2.9 - 53.3)
Fan Heater (Japan)	N/A	2.6 (1.6)	4.3 (2.6)
Oven	N/A (2.9)	4.7 (78.9)	129.1
Alzeta Prototype	0.7 - 9.6 (0.4 - 5.9)	1.2 - 8.6 (0.7 - 5.3)	2.2 - >27.5 (1.3 - >16.8)
Cyclonic Combustor	**0.3 - 1.3 (0.2 - 0.8)**	**0.2 - 0.7 (0.1 - 0.4)**	**1.6 - 5.9 (1 - 3.6)**

SUMMARY AND CONCLUSIONS

The technical approach to achieve ultra-low-emission combustion has been proved. This includes premixed high excess-air cyclonic combustion with flame-stabilization enhancement by a flame stabilizer, in conjunction with optimized nozzle velocity control.

Parametric studies were conducted on the test burner to explore the effects of major combustor configuration parameters and operating conditions on combustor performance. Test results have demonstrated that ultra-low-emission combustion has been achieved over a large range of operating parameters, as summarized below:

Firing Rate: 12 to 500 kW (60 to 450 kW for main burner alone)
NO_x: 0.3 to 1.0 vppm
NO_2: 0.1 to 0.4 vppm
CO: 1 to 3.6 vppm
THC: 0.4 to 3.0 vppm

The gas-fired cyclonic combustor has demonstrated excellent performance for ultra-low combustion emissions and a large turndown ratio. This technology, therefore, is an ideal candidate for direct-fired heating applications.

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