3.2.2.3

Surface Stabilized Combustion

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3.2.2.3-1 Introduction

Surface-stabilized combustion is a simple approach that can maximize the emissions benefit of lean fuel/air premixing by increasing flame stability, and doing so in a compact and flexible manner. ALZETA Corporation is developing a surface-stabilized combustion system for industrial turbine applications capable of sub-3 ppm emissions of oxides of nitrogen (NO_X) with simultaneous low emissions of carbon monoxide (CO) and unburned hydrocarbons (HC). The application of surface-stabilized combustion to gas turbines is being developed under the name nanoSTAR™. The development has been reported in a series of technical papers given at various ASME conferences[1].

Low emissions of oxides of nitrogen (NO_X), as well as carbon monoxide (CO) and unburned hydrocarbons can be achieved with thorough fuel/air mixing and control of the adiabatic flame temperature of that mixture below about 1920 K (3000 °F). One of the great difficulties with such lean premixed systems has been maintaining flame stability in the narrow flame temperature range between high NO_X production and lean flame extinction. Aerodynamically stabilized injectors have very narrow ranges of operation, necessitating multiple injector staging (up to four stages in some systems) or piloting[2]. When control of NO_x emissions is achieved without the use of steam or water injection, it is referred to as a dry method, such Dry Low NO_x, or DLN systems, have been successfully deployed to achieve sub-25 ppm NO_x emissions in several gas turbine applications, and in some cases much lower.

Surface-stabilized combustion is a simple approach that extends the operating range of lean premixed systems to achieve sub-3 ppm NO_x emissions. The technology has advanced through proof-of-concept testing in pressurized rigs and demonstration in a one megawatt test engine. Prototype injectors for small industrial turbines have been designed, built, and rig tested. Multiple injectors have been tested in an annular combustor with varied combustion air inlet temperatures under atmospheric and elevated pressures while work is progressing toward an engine demonstration.

3.2.2.3-2 Technology

The surface-stabilized combustion inherent in nanoSTAR injectors is best described as laminar blue-flame combustion stabilized by significant velocity gradients above a porous metal-fiber mat. The operation of this type of surface-stabilized combustion is characterized by the schematic to the left of figure 1, which shows premixed fuel and air passing through the metal fiber mat in two distinct zones.

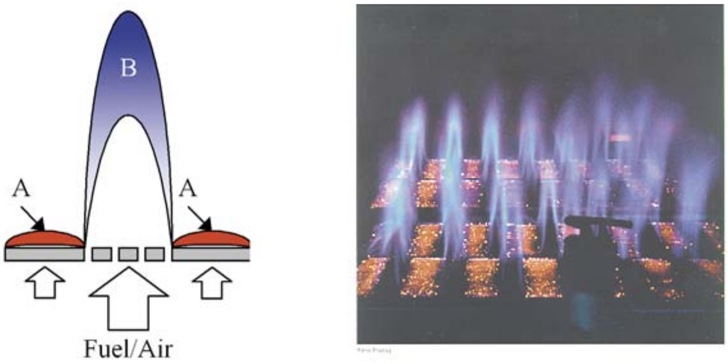

Fig.1. Surface-Stabilized Combustion (reproduced by permission of the publisher from American Society of Mechanical Engineers [ASME])

Source: S. J. Greenberg, N. K. McDougald, and L. O. Arellano, "Full-Scale Demonstration of Surface-Stabilized Fuel Injectors for sub-Three ppm NOx Emission," ASME Paper # GT2004-53629 (presented at the 2004 ASME Turbo Expo, Vienna, Austria, June 14-17, 2004).

In the porous-only zone true surface combustion (A) is realized. Under lean conditions this will manifest as very short laminar flamelets, but under rich conditions the surface combustion will become a diffusion-dominated reaction stabilized just over a millimeter above the metal matrix, which proceeds without visible flame and heats the outer surface of the mat to incandescence. This type of radiant surface combustion can be seen between the laminar flamelets to the right of figure 1.

Portions of the metal fiber mat are perforated to allow higher mass flux (B). In these zones stretched laminar flames are established that are anchored by the adjacent surface combustion. This produces the distinctive flame pattern seen in the right-hand picture of figure 1. The specific perforation arrangement and pattern control the size and shape of the laminar flamelets. The perforated zones operate at flow velocities of up to 10 times the laminar flame speed producing a factor of ten stretch of the flame surface and resulting in a large laminar flamelets. The alternating arrangement of laminar blue flames and surface combustion, allows high firing rates to be achieved before flame liftoff occurs, with the surface combustion stabilizing the long laminar flames by providing a pool of hot combustion radicals at the flame edges.

At atmospheric operation, nominal injector output would be 3.15 MW/m^2 (1.0 million $Btu/hr/ft^2$), so an injector with a fired area of .047 m^2 (0.5 ft^2) would have a capacity of 146.5 kW (500,000 Btu/hr). Assuming the firing rate of the injector increases linearly with pressure, the SFR remains constant as pressure increases. This results in a compact injector size for a given capacity in high pressure systems. Therefore the 146.5 kW (500,000 Btu/hr) injector at 0.1 MPa (1 atm) becomes nominally a 1,465 kW (5 million Btu/hr injector) at 1 Mpa (10 atm). Put another way, based on a gas turbine with a heat rate of 10,000 Btu/kilowatt-hour and a combustion pressure of 10 atmospheres, only about one square foot of injector surface area would be required for every megawatt of gas turbine output.

NanoSTAR injectors are constructed of small metal fibers which are compressed and sintered, resulting in an all-metal structure. This porous pad is perforated to produce a proprietary arrangement of perforation zones. The perforated metal fiber pads have a very low pressure drop but excellent flow uniformity. They also display excellent durability in fired service. In an atmospheric cycling test, a nanoSTAR metal fiber pad withstood over 15,000 ignition/cooling cycles over a 30-day period without a significant loss in operability. Further material and oxidation studies are being conducted in order to estimate injector life which is expected to exceed 8000 hours. Figure 2 depicts an injector in a gas turbine combustor liner.

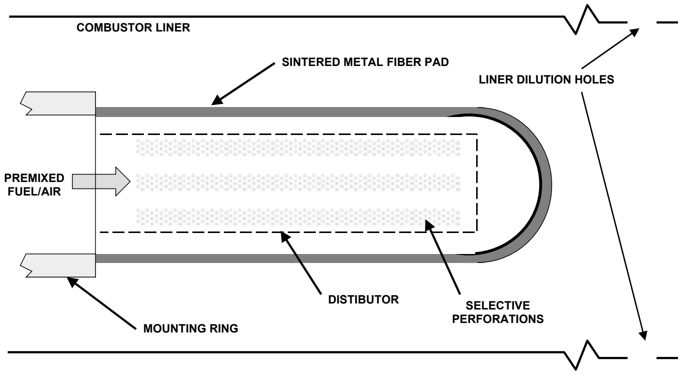

Fig. 2. Surface-Stabilized nanoSTAR Injector (reproduced by permission of the publisher from American Society of Mechanical Engineers [ASME])

Source: See fig. 1.

The laminar blue flame combustion zones created by the surface stabilization contribute to lower NO_X emissions in three ways. The dominant mechanism is the expected benefit from using a fully premixed fuel and oxidizer, resulting in a uniform temperature across the reaction zone, and lean burning, resulting in reaction temperatures below the 1920 K (3000 °F) limit for thermal NO_X formation. The second is the much lower residence time in the hot combustion zone. The peak temperatures are realized in the combustion front formed by each laminar flamelet which, like that of a Bunsen injector flame, is very thin. So the residence time in the peak flame temperature zone for a nanoSTAR injector is a fraction of that of a typical aerodynamically-stabilized injector. The third mechanism is a more rapid post-flame cooling of each blue-flame zone via the gas phase radiation mechanism. By spreading the flame over a larger surface, the gas layer thickness at any specific location on the injector is thin (relative to that of a conventional injector) and can more rapidly transfer energy as a result.

These mechanisms combine in a nanoSTAR injector to produce lower NO_X emissions than a typical lean premixed aerodynamically-stabilized injector. Figure 3 shows a comparison between nanoSTAR injector emission results from a high-pressure rig test and perfectly-premixed aerodynamically-stabilized emission results from a 1990 paper by Leonard and Correa[3]. In both cases the tests were conducted at 1.01 Mpa (10 atm) and 535-590 K (500-600 °F) inlet temperatures. A nanoSTAR injector firing in under atmospheric pressure in a quartz enclosure is shown in figure 4.

In addition to lower emissions with a wide turndown window, nanoSTAR injectors can be designed to fit within existing combustor liners and fitted to existing fuel/air premixers without extensive modification to the combustion equipment or pressure case. Furthermore, they require no extraordinary control schemes or equipment beyond that which would be required for an aerodynamically-stabilized lean-premixed injector.

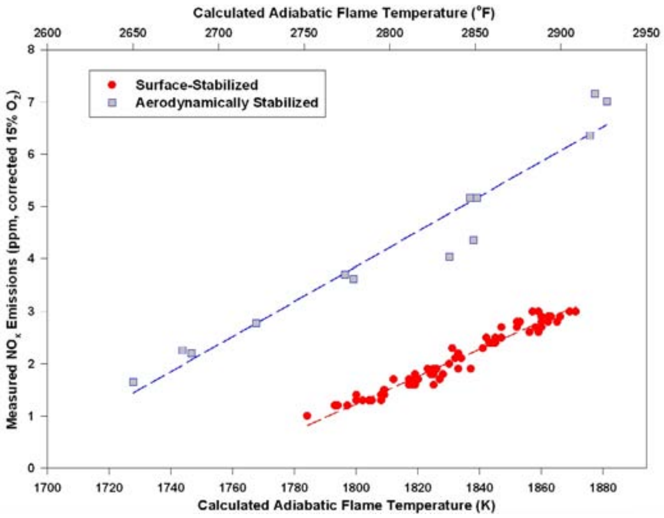

Fig. 3. Surface-Stabilized Compared to Aerodynamically-Stabilized Emission Results at 1.01 MPa (10 atm) Pressure and 535-590 K (reproduced by permission of the publisher from American Society of Mechanical Engineers [ASME]).

Source: See fig. 1.

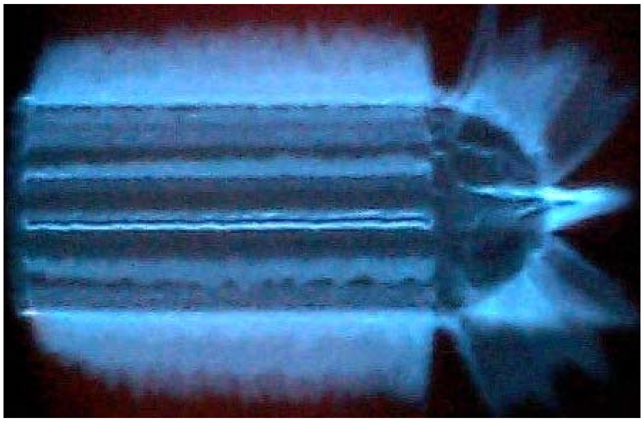

Fig. 4. Surface-Stabilized nanoSTAR Injector (reproduced by permission of the publisher from American Society of Mechanical Engineers [ASME]).

Source: See fig. 1.

3.2.2.3-3 Experimental Results

The nanoSTAR injectors have been extensively tested in sub-scale rigs over a broad range of inlet temperatures and operating pressures. Representative results are shown in figure 5 comparing single and dual injector results at 1.2 MPa (12 atm). These results confirmed that injectors could be fired in close proximity without impacting emissions or operability clearing the way for full-scale annular combustor testing.

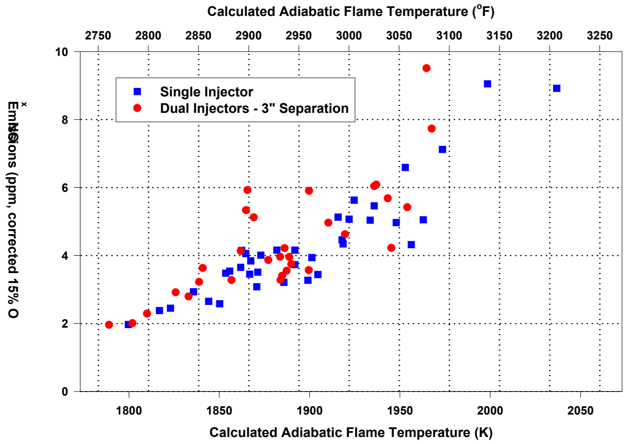

Fig. 5. Comparison of Sector Rig NO_X Data with Single Injector Rig Data at 1.2 MPa (12 atm) Pressure and 640 K (690°F) Inlet Temperature (reproduced by permission of the publisher from American Society of Mechanical Engineers [ASME]).

Source: See fig. 1. above.

Fig. 6. Interior of Full Scale Annular Combustor during Atmospheric Testing (reproduced by permission of the publisher from American Society of Mechanical Engineers [ASME]).

Source: See fig. 1. above.

A full-scale annular combustor was fitted with twelve equally spaced nanoSTAR injectors. The assembly was tested under atmospheric conditions which allowed for visual observation of the fired injectors as in figure 6. Four thermocouple rakes recorded temperatures around the combustor outlet to create the outlet profile shown in figure 7. The outlet profile was uniform with an overall pattern factor of 0.16 that is well within acceptable limits.

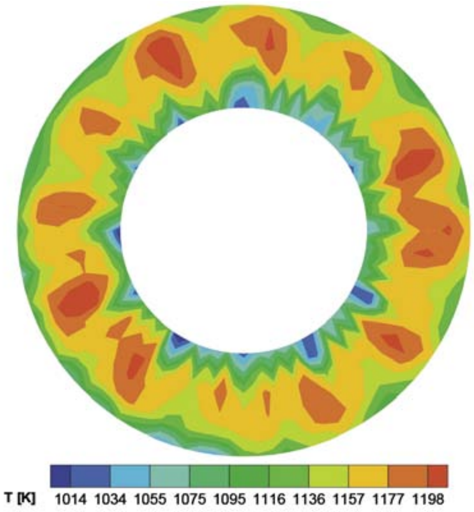

Fig. 7. Plot of Temperature Contours at Exit Plane of Annular Combustor at Atmospheric Pressure and 650 K (700°F) Inlet Temperature (reproduced by permission of the publisher from American Society of Mechanical Engineers [ASME]).

Source: See fig.1. above.

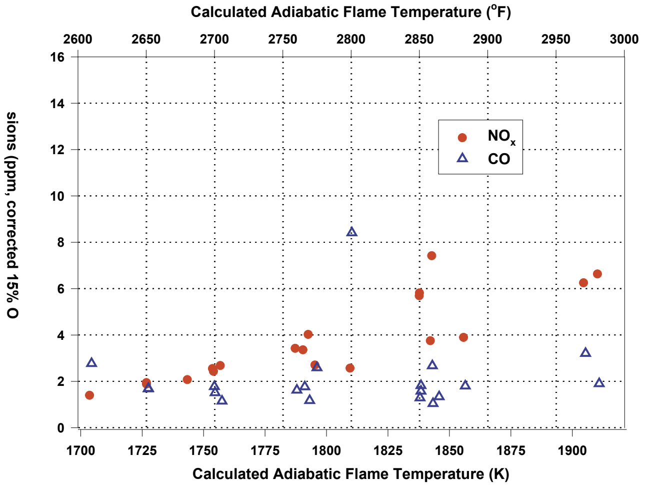

Fig. 8. Emissions Data Collected During Full Scale Pressurized Testing at 0.5-1.2 MPa (5-12 atm) Pressure and 475-700 K (400-800°F) Inlet Temperature (reproduced by permission of the publisher from American Society of Mechanical Engineers [ASME]).

Source: See fig. 1. above.

The full-scale combustor was installed in a high pressure test cell and operated at pressures between 0.5-1.2 MPa (5-12 atm) with inlet air temperatures between 475-700°K (400-800°F). Emissions data collected during these tests are presented in figure 8. The results were consistent with previous sub-scale results and provided data necessary to design an engine-ready combustor.

3.2.2.3-4 Conclusions

Surface stabilized combustion extends the lean premixed combustion stability allowing ultra-low emissions to be realized under small industrial gas turbine operating conditions. ALZETA's nanoSTAR technology has progressed through a series of sub-scale and full-scale rig tests consistently demonstrating ultra-low NO_x emissions of less than 3 ppm (corrected to 15% O_2) over a broad range of operating conditions. The next stage in the development is an engine demonstration which should be completed by the end of 2005.

3.2.2.3-5 Notes

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1. C.K. Weakley, S. J. Greenberg, R. M. Kendall, N. K. McDougald, and L. O. Arellano, "Development Of Surface-Stabilized Fuel Injectors With Sub-Three ppm NO_X Emissions," ASME Paper # IJPGC2002-26088 (presented at the 2002 International Joint Power Generation Conference, Phoenix, AZ, June 24-26, 2002; Greenberg, S. J.); N. K. McDougald, C. K. Weakley, R. M. Kendall, and L. O. Arellano, "Surface-Stabilized Fuel Injectors With Sub-Three ppm NO_X Emissions for a 5.5 MW Gas Turbine Engine," ASME Paper # GT2003-38489 (presented at the 2003 ASME Turbo Expo, Atlanta, GA, June 16-19, 2003); S. J. Greenberg, N. K. McDougald, and L. O. Arellano, "Full-Scale Demonstration of Surface-Stabilized Fuel Injectors for sub-Three ppm NOx Emission," ASME Paper # GT2004-53629 (presented at the 2004 ASME Turbo Expo, Vienna, Austria, June 14-17, 2004.).
2. C. L. Vandervort, "9 ppm NO_X/CO Combustion System for "F" Class Industrial Gas Turbines," *ASME J. of Engineering for Gas Turbines and Power* 123 (2001): 317-321.
3. G. L. Leonard and S. M. Correa, "NO_X Formation in Premixed High-Pressure Lean Methane Flames," *Fossil Fuel Combustion Symposium 1990*, S. N. Singh, ed. (New York: American Society of Mechanical Engineers, 1990): 69-74.

BIOGRAPHY

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Since July 2000, Dr. McDougald has been leading ALZETA's effort to develop nanoSTAR, an ultra-low emissions combustion system for gas turbines. The nanoSTAR is a surface-stabilized lean premixed combustion technology that provides ultra-low NO_x emissions while avoiding unstable combustion dynamics. As Director of Product Development, he is responsible for management and technical support for ALZETA's existing and emerging combustion products.