Ultra Low Emissions Combustor with Non-Premixed Reactants Injection[*]

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This paper describes a novel Stagnation Point Reverse Flow (SPRF) combustor concept that can burn gaseous or liquid fuels in premixed or non-premixed modes of combustion with ultra low NOx emissions. The combustor consists of a tube with open and closed ends. Contrary to most combustors, the reactants and products enter and leave this combustor at the same (open) end. In the investigated configuration, the reactants are injected along the combustor center line, moving towards the closed end, where the flow velocity must be zero. This creates a low velocity region towards the closed end of the combustor that helps stabilize the combustion process. Furthermore, the presence of a closed end forces the generated combustion products and burning gas pockets to reverse their flow direction and move towards the open (exhaust) end of the combustor. Thus, a portion of the hot products, laden with radicals, are entrained back into the incoming reactants to form a more chemically reactive mixture. The presence of radicals in the mixture lowers its ignition temperature and, thus, the lean blowout limit of the combustor. Thus, the SPRF combustor's geometry produces a combination of stagnation and reverse flow entrainment that allows this combustor to operate stably at very low temperatures with ultra low NOx emission in the 1 ppm range and below. It is also shown that these low NOx emissions can be attained with premixed or non-premixed modes of combustion. Finally, it is shown that the developed combustor can operate with high combustion intensities, in the 30-40 MW/m^3 range at atmospheric pressure, without experiencing combustion instabilities.

I. Introduction

The ongoing tightening of emissions regulations have stimulated studies of approaches for reducing NOx, CO and unburned hydrocarbon (UHC) emissions from combustion systems. These studies have primarily focused on elucidating NOx formation mechanisms and on the development of practical approaches for reducing NOx emissions. Identified mechanisms include the thermal (Zeldovich), prompt and N_2O routes of NOx formation.[1] Approaches for NOx reduction include air and fuel staging,[2,3] lean premixed combustion,[4] water injection,[5] catalytic combustion,[6] arrays of fuel injectors to enhance fuel-air mixing,[7,8] external exhaust gas recirculation (EGR)[9] and internal recirculation of combustion products and reacting gases within the combustor.[10-11] The goal in most of these approaches is to burn the fuel using reaction routes that minimize NOx formation, primarily focusing on burning the fuel at low temperatures, e.g., below 1700K where NOx formation due to the thermal mechanism is minimal. Thus, most of these methods seek to avoid the formation of nearly stoichiometric, combustible gas pockets that would burn at high temperature and, therefore, significantly increase NOx emissions.

Consequently, it appears that NOx emissions can be minimized if all the fuel could be burned in a lean mixture with uniform properties at temperatures below the threshold value where the thermal NOx formation mechanism becomes important. It is important however, for practical considerations, that combustion take place in a *stable* manner. In a recent theoretical paper, Kalb *et al.*[11] predicted that NOx emissions could be reduced to ultra low levels

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[*] Patents applications have been filed to protect the various configurations of the combustor described in this paper.
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by mixing a *combustible* mixture with hot combustion products laden with radicals prior to combustion. They argued that the presence of radicals in the mixture lowers its ignition temperature and, thus, allows *stable* combustion of mixtures that would otherwise not be flammable. Thus, premixing the reactants with radicals to lower the combustion process temperature should allow low temperature combustion with ultra low NOx emissions. Finally, they proposed a combustor design that would allow premixing of reactants with radicals by use of periodically spaced injectors (around the circular periphery of a combustor) that supply jets of a combustible mixture into the combustor. The current paper describes the design and experimentally determined performance of a radically different combustor concept that uses its geometry to force premixing of the incoming reactants with hot products and radicals prior to combustion and to provide means for stabilizing the combustion process. It will be shown that this combustor can operate *stably* with ultra low NOx emissions while burning gaseous or liquid fuels in a premixed or a non-premixed mode of combustion.

II. SPRF Combustor Design

The primary objective of this study was to develop a combustion system that can operate with ultra low NOx emissions (i.e., 1 ppm or below at 15% O_2) by burning fuel stably at sufficiently low temperatures. The result is the combustor shown in Figure 1 and Figure 2, which also show some of the instrumentation used in this study. The combustor consists of a tube with close and open ends. Reactants are supplied through an injection system at the center of the open end, which can provide a combustible stream of premixed reactants through its *annular* opening or separate fuel and air streams through the central and annular tubes, respectively.

The reactants are injected along the combustor's center line and flow towards its closed end, where the velocity must be zero. Consequently, the velocity must decrease as the flow approaches the closed end. This establishes a low velocity region in the vicinity of the closed end that can help to stabilize the combustion process. Since the generated products and burning gas pockets can not leave the combustor through its closed end, they must reverse their flow direction and exit the system through the annular opening around the injection system. As the stream of hot products laden with radicals flows out of the combustor (Figure 2), it must mix with the incoming reactants. Mixing with hot products increases the reactant temperature and the presence of radicals in the resulting mixture should lead to reduced ignition temperatures.

In summary, the developed combustor uses its unique geometry to: 1) force the incoming reactants to mix with exiting products and radicals prior to ignition and 2) establish a low velocity region downstream. These two features are incorporated in the combustor's chosen name, i.e., the Stagnation Point Reverse Flow (SPRF) combustor. The combination of these two features is expected to allow the combustor to operate *stably* at lower inlet temperatures and/or lower fuel-air ratios, and, thus, produce lower NOx emissions.

To be practical, the SPRF combustor should also operate with low CO and unburned hydrocarbon emissions, high combustion efficiency, low pressure losses and no acoustic instabilities over a wide range of operating conditions. It would be also highly desirable if the combustor can operate with these features in a *non-premixed* mode to avoid some of the drawbacks of previously developed low NOx, lean, premixed combustors, for example, flashback and the additional hardware required to pre-vaporize (and premix) liquid fuels.

The photograph of the operating quartz SPRF combustor shown in Figure 2 captures its main features: the (dark) stagnation flow region at the bottom, the (blue) combustion region in the middle, the reverse flow of hot products and reactants near the wall, and the (dark) flame standoff distance downstream of the injection system where the reactants mix with hot products prior to ignition. The main difference between premixed and non-premixed operation is also illustrated in the figure (left side). When operating in a premixed mode, ignition can occur in the shear layer between the incoming reactants and the exiting products at some distance downstream of the injection plane. When operating in a non-premixed mode, two shear layers are established in the combustor: one between the co-flowing fuel and air streams, and the other between the counter-flowing air and product gas streams. To operate with low NOx emissions in this configuration, the mixing between the fuel and air must create a lean combustible mixture that would be then ignited at low temperature by the mixture of air, radicals and hot products generated via mixing in the outer shear layer.

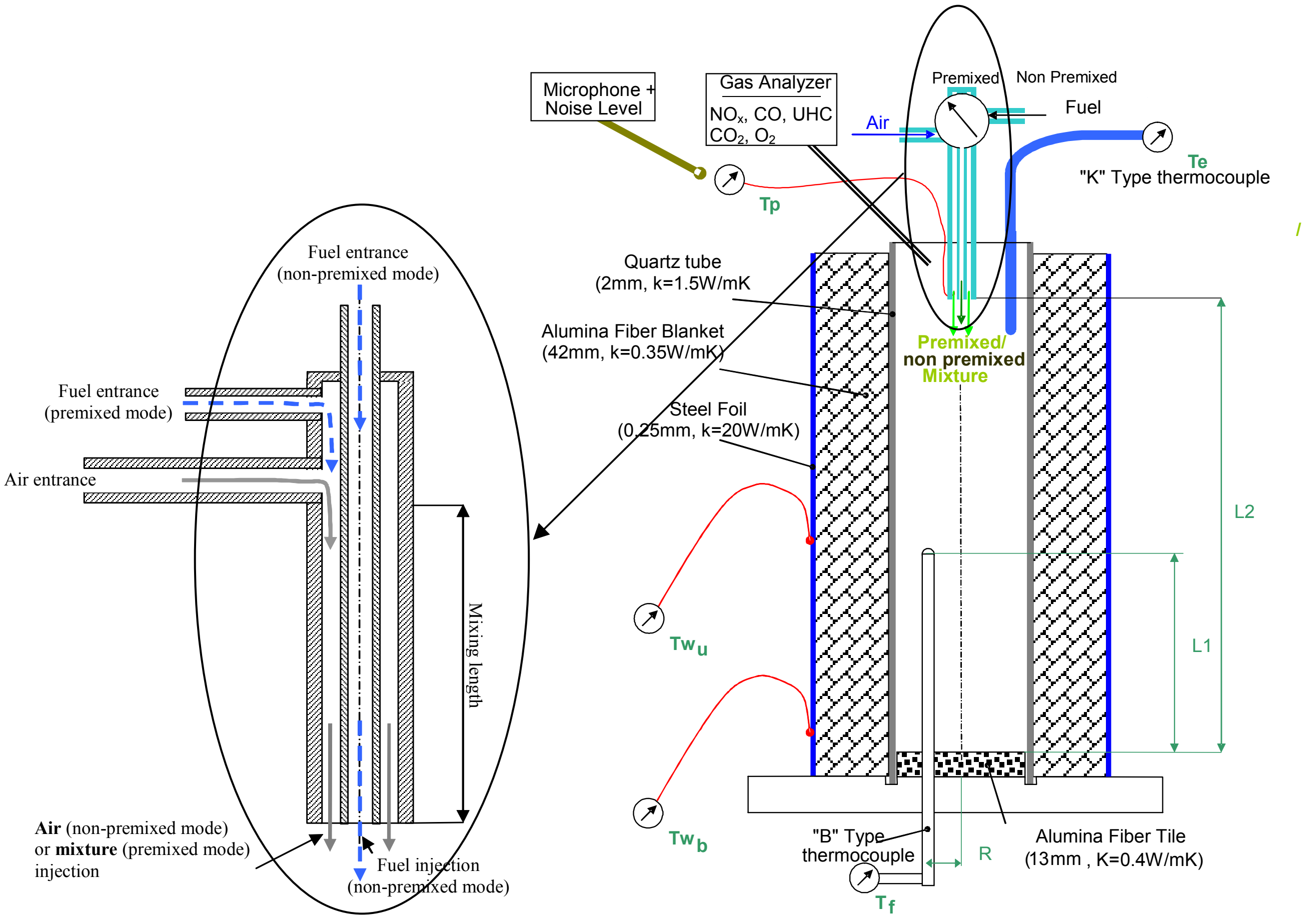


Figure 1. A schematic of the investigated SPRF combustor.

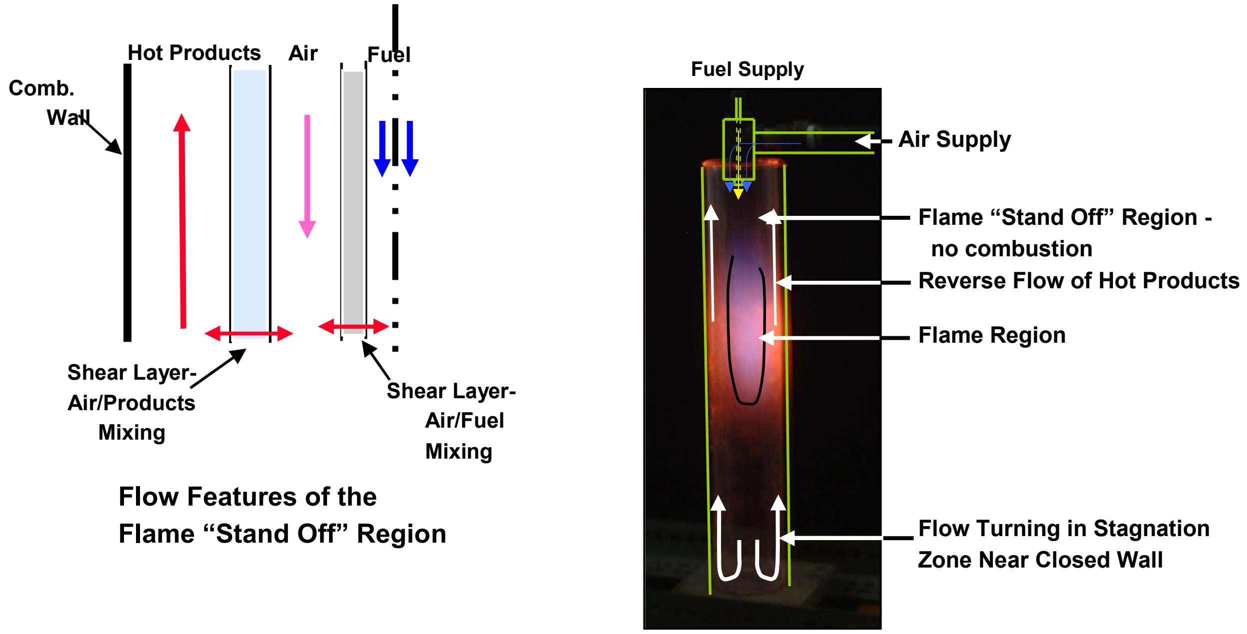
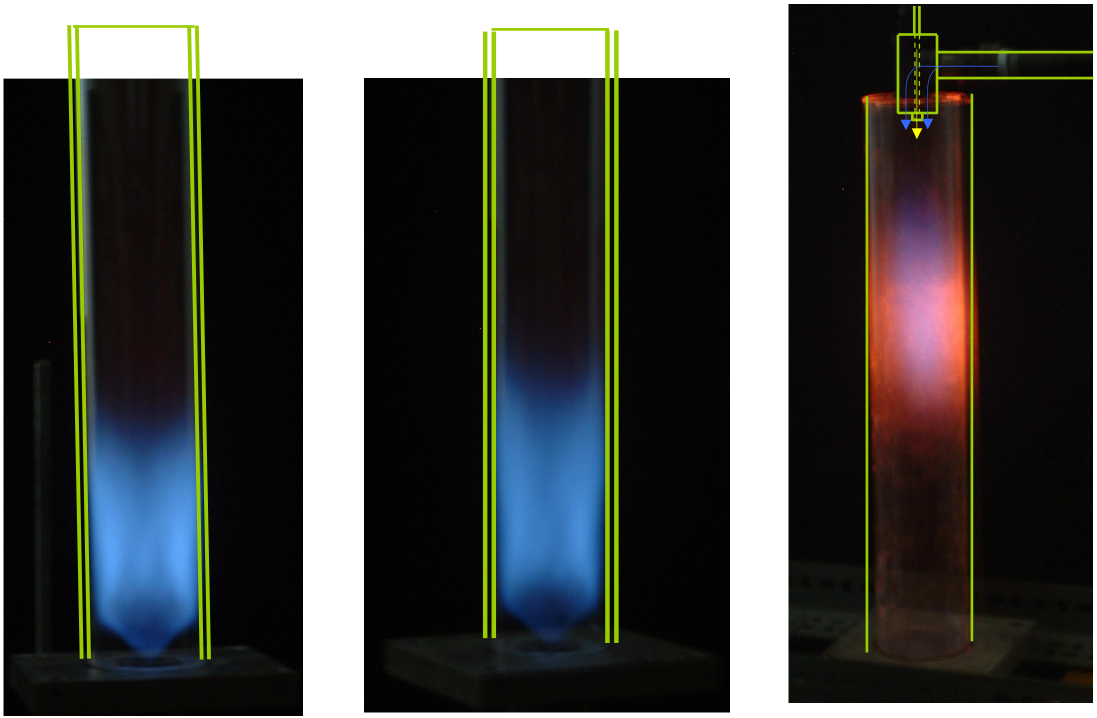


Figure 2. A photograph of a quartz SPRF combustor in operation (right) and a qualitative description of the flow features of the flame "stand off" region (left).

III. SPRF Combustor Performance

In order to evaluate the ability of the new combustor design to operate with ultra-low NOx emissions, experiments were performed in both premixed and non-premixed modes of combustion. For comparison, experiments were also conducted in fully and partially premixed, swirl-stabilized combustors, which are extensively used in gas turbine and industrial systems. All the combustors studied here were operated at atmospheric pressure and utilized identical quartz tubes to form the combustor walls. The quartz walls were un-cooled, and in most cases surrounded by ceramic insulation. Figure 3 presents photographs of three of these systems during operation (without insulation). In the two swirl combustors on the left, the degree of premixing was controlled by varying the location of fuel injection upstream of the combustor. The third image in the figure shows the SPRF combustor burning fuel in a non-premixed mode of operation. Fuel and air flow rates were monitored with mass flow meters, and emission measurements were made with a sampling probe placed near the combustor exit and a Horiba (PG-250) gas analyzer.



Premixed Swirl Combustor

Partially Premixed Swirl Combustor

Stagnation Point, Reverse Flow Combustor-Non Premixed

Figure 3. Photographs of the investigated combustors when burning natural gas.

The measured NOx emissions (corrected to 15% O_2) for the different combustor configurations (and insulated in all cases) are shown in Figure 4 as a function of the overall equivalence ratio. The results are for natural gas, with fuel flow rates varied between 0.65 g/sec at Φ=1 and 0.42 g/sec at Φ=0.68. One important observation is that the minimum NOx emissions of the SPRF combustor are roughly the same (in fact slightly lower) than those produced by the swirled, premixed combustor. In addition, the SPRF combustor produces comparable, ultra low NOx emissions, i.e., of the order of 1 ppm, when operated either premixed or non-premixed. In contrast, the traditional swirl combustor has significantly higher NOx emissions when operated partially premixed compared to its premixed emissions. Also unlike traditional combustors, the NOx emissions of the SPRF combustor at higher equivalence ratios are even lower for non-premixed operation than when it is running premixed. The data presented in Figure 4 demonstrate that the SPRF combustor can be operated in a non-premixed mode of combustion with ultra low NOx emissions.

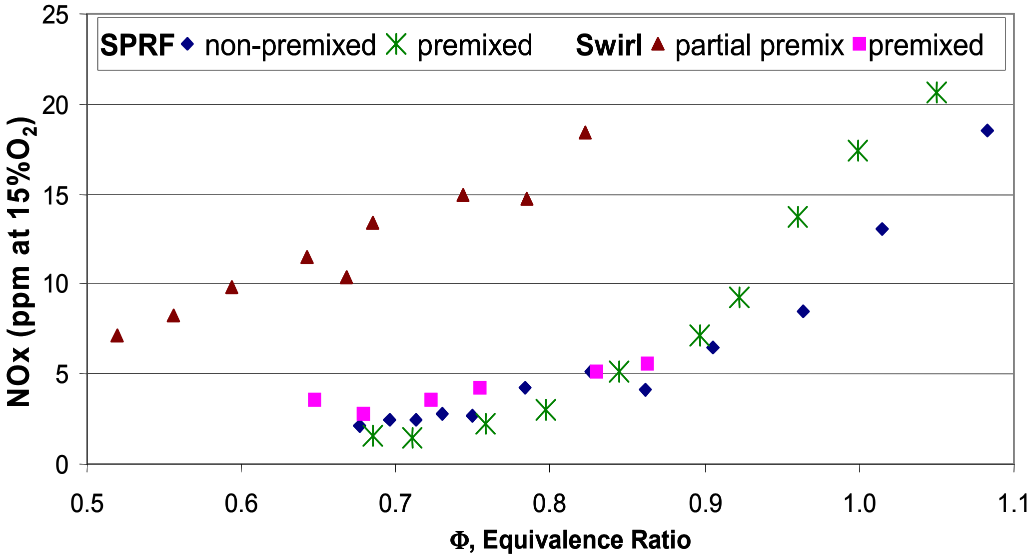


Figure 4. Dependence of NOx emissions on the global equivalence ratio of injected reactants.

Similar measurements of the combustor emissions were made when the SPRF combustor was operated with liquid heptane fuel. These are compared with those produced for combustion of natural gas at different equivalence ratios and loads in Figure 5. As evidenced in the figure, the SPRF configuration is capable of burning liquid heptane that has been directly injected into the combustor (i.e., without prevaporization) with minimum NOx emissions comparable to those produced during premixed and non-premixed combustion of natural gas. The results also indicate that increasing the injection air velocity at a given equivalence ratio (and, thus, the combustor load) is accompanied by a NOx emissions reduction. Finally, it should be noted that that the combustion intensities of the SPRF combustor when burning heptane with an air injection velocity of 148 m/sec at the minimum and maximum equivalence ratios (see Figure 5) were 28 and 36 MW/m^3, respectively. We have since obtained similar results with much lower air injection velocities.

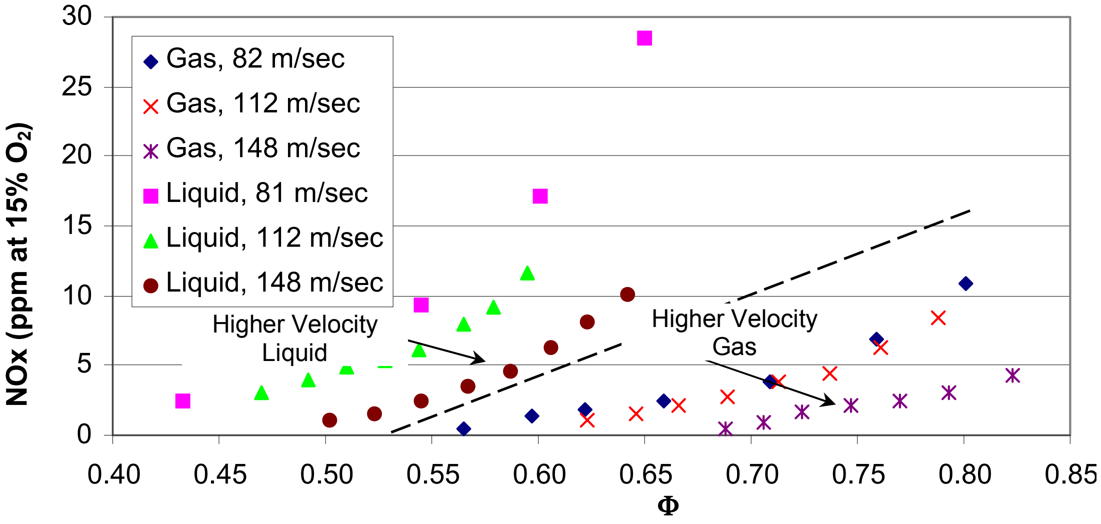


Figure 5. Comparison of the equivalence ratio dependence of the NOx emissions from the SPRF combustor when burning heptane and natural gas at different loads.

To understand the flame structure, a thermocouple (see Figure 1) was vertically traversed through the combustor at various radial locations to determine the average temperature distribution within the combustor. Such measured (uncorrected) temperature profiles obtained in a test in which natural gas was burned in the SPRF combustor at an equivalence ratio 0.59, methane flow rate of 0.4 g/sec and air injection velocity of 116 m/sec are shown in Figure 6 (left). Assuming that the time-averaged flow field is axi-symmetric, the measured temperature profiles were used to "construct" the temperature field within the combustor, as shown in the right half of Figure 6. For the indicated operating conditions, the maximum (average) temperature within the combustor did not exceed 1500K, which is well below the threshold where thermal NOx formation is important. The data also show the presence of a fairly broad maximum temperature region where the flow velocities are expected to be low (near the closed end of the combustor). Gases at this maximum temperature are also present along the outer combustor walls where the products are flowing out of the combustor towards its exit plane. The temperature data also show that the out flowing products preheat the incoming reactants to a temperature of approximately 700K. Finally, the hatched vertical line on the left is a calculated adiabatic flame temperature based upon the equivalence ratio and (measured) inlet reactants temperature. The difference between the calculated adiabatic flame temperature and the measured maximum temperature is a measure of the combustor heat losses.

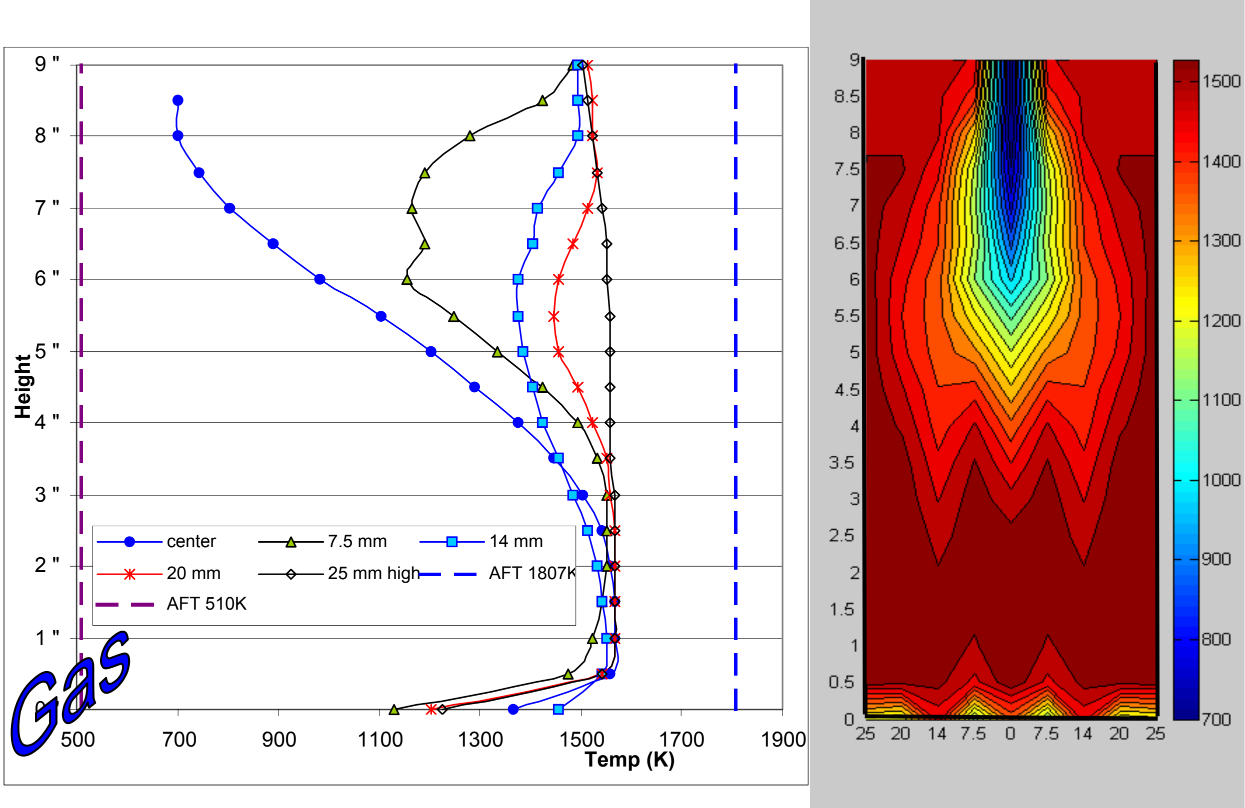


Figure 6. Measured steady temperature distributions within the SPRF combustor during the combustion of natural gas at an equivalence ratio of 0.59, flow rate of 0.4 g/sec and air injection velocity of 116 m/sec.

It is interesting to compare the temperature map in Figure 6 with photographs of the flame emission from the SPRF combustor when burning natural gas in a premixed mode. The flame images of Figure 7 (for two equivalence ratios, 0.55 and 0.74) suggest that in both cases there is a stand-off distance between the location where the reactants are injected and the "initial" point where the flame appears. This stand-off distance (or flame liftoff) significantly increases as the equivalence ratio of the mixture decreases. At the leanest condition (Φ=0.55, Figure 7 right), the image indicates that the flame (or combustion process) is likely stabilized in a region in the immediate vicinity of the closed end of the combustor, corresponding to the region of maximum temperature in Figure 6. Furthermore, Figure 6 shows that gases at roughly the maximum temperature are present near the outer wall of the combustor where a flame is absent in both images of Figure 7. This indicates that this region is occupied by hot products, which have reversed direction and are moving upward towards the open end of the combustor.

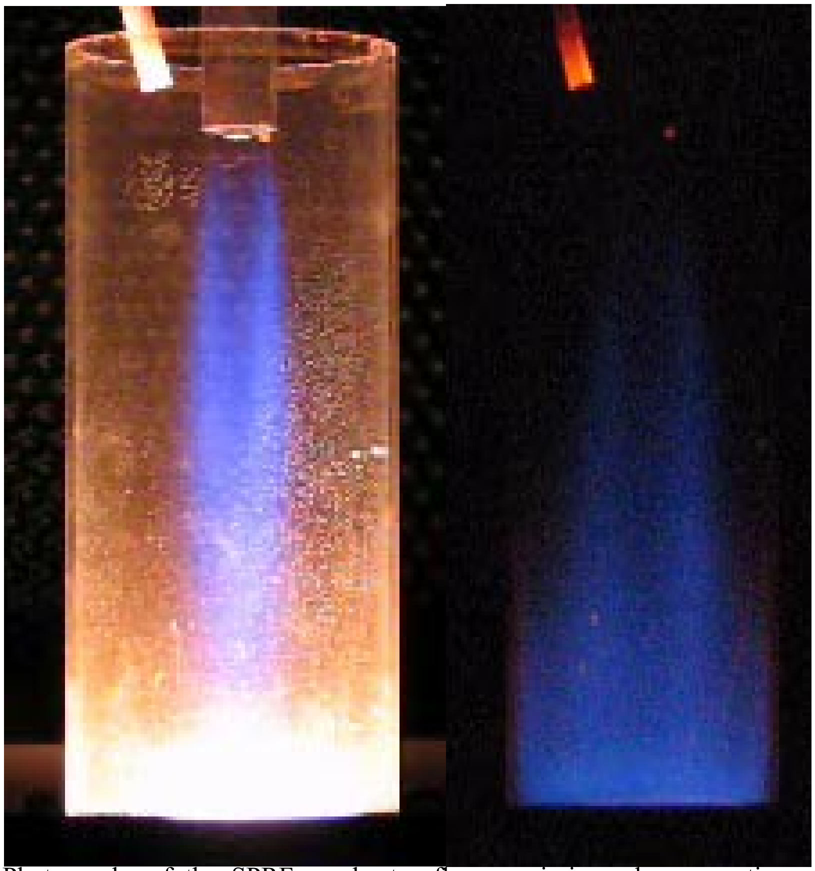


Figure 7. Photographs of the SPRF combustor flame emission when operating premixed at an equivalence ratios of: 0.74 (left) and 0.55 (right).

IV. Summary

This paper describes a novel combustor design that can operate with ultra-low NOx emissions while burning gaseous or liquid fuels in premixed or non-premixed modes of combustion. In fact, it has been shown that practically the same NOx emissions are attained in both modes of operation. This is significant because applications of lean, premixed combustors in gas turbines and industrial processes have generally experienced operability problems due to flashback, combustion instabilities and lean blowout. This also has implications for aircraft engines, where there has been reluctance to introduce premixed (liquid fueled) combustion systems due to safety considerations.

While this paper focused primarily on NOx emissions, it should be noted that CO emissions measured in subsequent tests were below 10 ppm (corrected to 15% O_2) at the conditions corresponding to NOx emissions in the 1 ppm range. Furthermore, none of the SPRF combustors investigated under this program have experienced combustion instabilities, and non-premixed mode operation was generally quieter than premixed mode operation.

In summary, this paper describes a novel and *very simple* combustor concept that can operate stably over a large range of operating conditions with ultra-low emissions without experiencing combustion instabilities. The SPRF combustor concept should enable land-based gas turbines and aircraft engines to operate with low emissions, even when employing a non-premixed mode of combustion that increases safety and operability. The SPRF combustor concept should be also suitable for application in energy intensive industrial processes and a wide range of domestic, commercial and industrial heating processes.

Acknowledgements

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