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## Lean Premixed Combustion Stabilized by Low Swirl A Promising Concept for Practical Applications

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### Abstract

Since its inception [Chan et al. 1992], the low-swirl burner (LSB) has shown to be a useful laboratory apparatus for fundamental studies of premixed turbulent flames [e.g. Cheng 1995]. The LSB operates under wide ranges of equivalence ratios, flow rates, and turbulence intensities. Its flame is lifted and detached from the burner and allows easy access for laser diagnostics. The flame brush is axisymmetric and propagates normal to the incident reactants. Therefore, the LSB is well suited for investigating detailed flame structures and empirical coefficients such as flame speed, turbulence transport, and flame generated turbulence.

Due to its capability to stabilize ultra-lean premixed turbulent flames ( $\phi \approx 0.55$ ), the LSB has generated interest from the gas appliance industry for use as an economical low- $\text{NO}_x$  burner. Lean premixed combustion emits low levels of  $\text{NO}_x$  due primarily to the low flame temperature. Therefore, it is a very effective  $\text{NO}_x$  prevention method without involving selective catalytic reduction (SCR), fuel-air staging, or flue gas recirculation (FGR). In the gas turbine industry, substantial research efforts have already been undertaken and engines with lean premixed combustors are already in use. For commercial and residential applications, premixed pulsed combustors and premixed ceramic matrix burners are commercially available. These lean premixed combustion technologies, however, tend to be elaborate but have relatively limited operational flexibility, and higher capital, operating and maintenance costs. Consequently, these industries are continuing the development of lean premixed combustion technologies as well as exploring new concepts. This paper summarizes the research effects we have undertaken in the past few years to demonstrate the feasibility of applying the low-swirl flame stabilization method for a wide range of heating and power generation systems.

The principle of flame stabilization by low-swirl is counter to the conventional high-swirl methods that rely on a recirculation zone to anchor the flame. In LSBs, flow recirculation is not promoted to allow the premixed turbulent flames to propagate freely. A LSB with an air-jet swirler (Figure 1) is essentially an open tube with the swirler at its mid section. The small air-jets generate swirling motion only in the annular region and leaving the central core of the flow undisturbed. When this flow exits the burner tube, the angular momentum generates radial mean pressure gradient to diverge the non-swirling reactants stream. Consequently, the mean flow velocity decreases linearly. Propagating against this decelerating flow, the flame self-sustains at the position where the local flow velocity equals the flame speed,  $S_f$ . The LSB operates with a swirl number,  $S$ , between 0.02 to 0.1. This is much lower than the minimum  $S$  of 0.6 required for the high-swirl burners. We found that the swirl number needed for flame stabilization varies only slightly with fuel type, flow velocity, turbulent conditions and burner dimensions (i.e. throat diameter and swirl injection angle).

Under the sponsorship of US Department of Energy, Energy Laboratory Research, we formed a partnership with Teledyne Laars of Moorpark California to explore the LSB's commercial potential for natural gas pool heaters. Laboratory experiments [Yegian and Cheng, 1998] show that a small LSB (5.28 cm ID) operates reliably within confinements of different sizes (10 to 20 cm ID). Tests performed in a water heater simulator (15-18 kW) demonstrate that the optimum operating condition of a LSB is at  $\phi = 0.85$  where  $\text{NO}_x$  and CO emissions are 25 ppm (both corrected to 3%  $\text{O}_2$ ). An important objective of this research is to develop a guide-vane swirler to replace the air-jets. A guide-vane swirler is preferred because it does not require a separate air source for the swirl flow. The design we have finalized and tested is shown schematically in Figure 2. Unlike conventional designs, this guide-vane swirler does not have a center hub to promote the formation of recirculation. It has instead an open center tube through which the center core of the reactants stream flows straight through. Swirling motion is generated by the guide-vane fitted within the annular region. To equalize the pressure drops across the

center tube and the guide-vanes, a screen or perforated plate covers the center tube opening. This screen also serves to generate turbulence. As seen from the photographs of Figure 1 and 2, the flame generated by the guide-vane swirler looks almost identical to the one produced in the air-jet LSB.

The performances of the two LSBs in a water heater simulator are compared in Figure 3. It is apparent that the system efficiencies and NO emissions are almost identical, both achieving close to 80% efficiency for  $0.7 < \phi < 0.9$  with NO less than 10 ppm at  $\phi < 0.85$ . The guide-vane swirler, however, offers significant improvement in CO emissions because it does not have the diluting effect of the air-jet swirler. The operating range of the guide-vane LSB, is also quite large (12 to 120 kW for  $0.60 < \phi < 1.0$ ). A prototype guide-vane LSB with a slightly larger diameter (7.5 cm) has been successfully tested in a 120 kW pool heater prototype.

These results have encouraged us to pursue further development of the LSB for larger capacity systems such as commercial furnaces and boilers. To allow flexibility in exploring the operating conditions and characteristics of large LSBs, we began by scaling the air-jet LSB. Using a constant velocity approach, the large capacity LSB we have designed (10.16 cm ID) is a linear scaled-up version of the smaller LSB (5.28 cm ID) used in the water heater simulator. The operating regimes of the large burner have been investigated at the Furnace Simulator Facility at University of California Irvine Combustion Laboratory and found to be stable over an input power range from 100 to 600 kW. These tests demonstrate the validity of using the constant velocity approach in scaling the LSB. The non-dimensional swirl number for the larger LSB is constant for the input power range we have investigated. However, it is higher than that of the smaller burner. This is attributed to the fact that the swirl rate does not scale with velocity, instead, it scales with the residence time of the swirl air within the burner's exit tube. The NO<sub>x</sub>, CO and UHC emissions of the large LSB were also determined and compared to those of a small LSB. The test matrix was limited to  $\phi = 0.8$  (25% excess air) at various input powers. As showed in Figure 4, the NO<sub>x</sub> emissions of both the large and the small LSBs average about 14 ppm (3% O<sub>2</sub>) over the entire input power range of 15 to 600 kW. Therefore, NO<sub>x</sub> emission of LSB is independent of burner size and combustion chamber geometry. On the other hand, the CO and UHC emission showed a strong dependence on burner chamber coupling. Both sets of data show that a minimum input power is needed in order to keep CO emission below 25 ppm (corrected to 3% O<sub>2</sub>) and UHC concentrations at the undetectable level. When operating above the minimum input power, the performance of the LSB is very encouraging. With NO<sub>x</sub> at 14 ppm, CO at 25 ppm, and UHC at an undetectable level, the LSB can meet many stringent air-quality rules for US urban centers.

More recently, we have initiated an effort to explore the feasibility of low-swirl flame stabilization concept for gas turbines. The 7.5 cm ID prototype low-swirl gas turbine injector uses an air-jet swirler. It also incorporates a premixer and a perforated screen to control the air split between the injector and the combustor liner. Preliminary test results of this injector in the Combustion Test Cells at Solar Turbines of San Diego, California are very encouraging. The low-swirl injector operated at pressures up to 4 atmospheres and with preheated air of 500K. Tests will be continued to investigate the performance of the low swirl injector at pressures up to 15 atmospheres.

These investigations have demonstrated that the LSB is a promising concept for use in a variety of heating and power generating systems.

#### References

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- Yegian, D. T. and Cheng, R. K. (1998). Development of a Lean, Premixed, Low-Swirl Burner for Low NO<sub>x</sub> Practical Applications, to appear *Combustion Science and Technology*

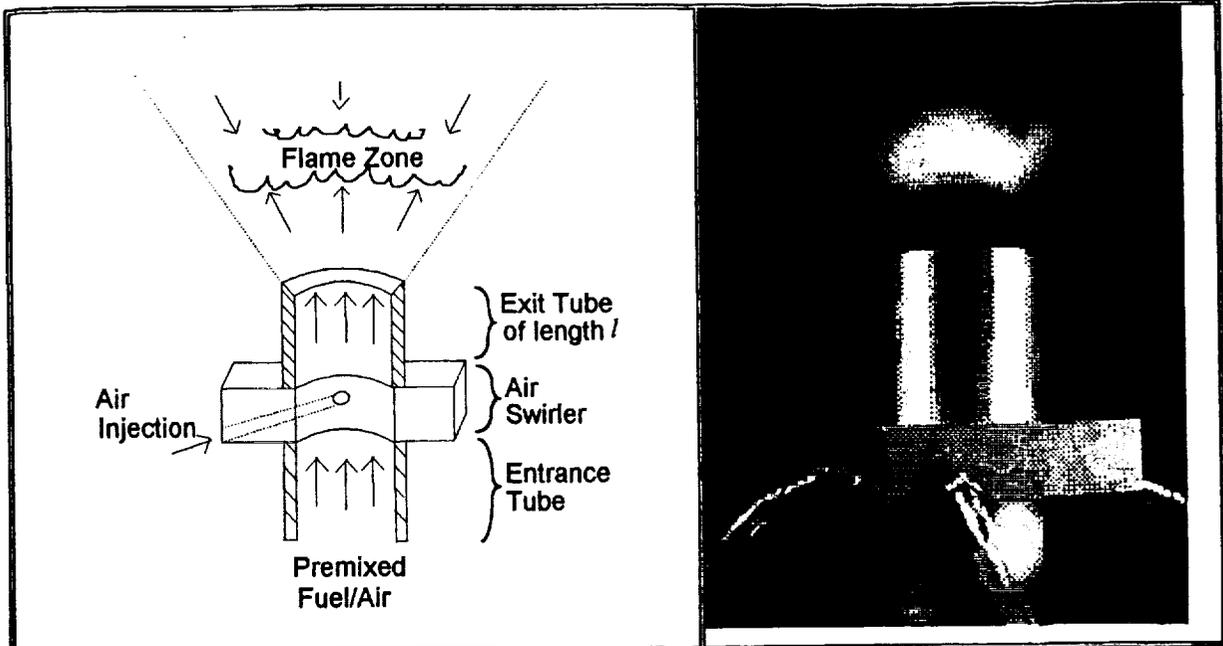


Figure 1 Schematics of a low swirl burner fitted with an air-jet swirler

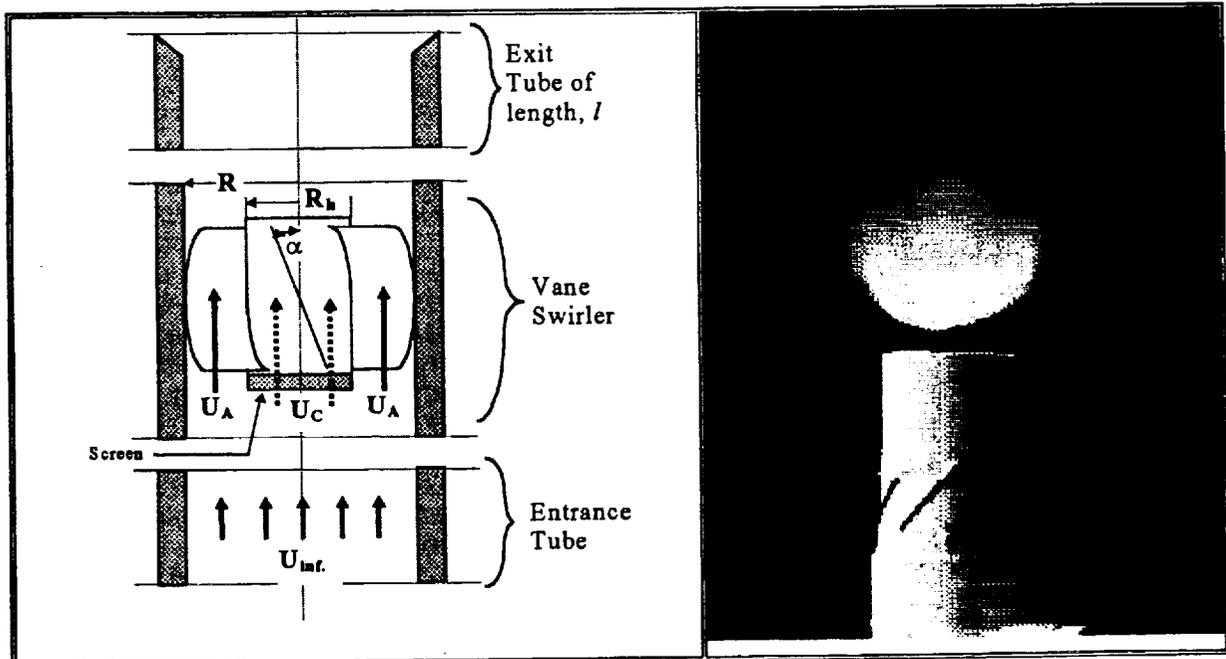


Figure 2 Schematics of a low swirl burner fitted with a guide-vane swirler

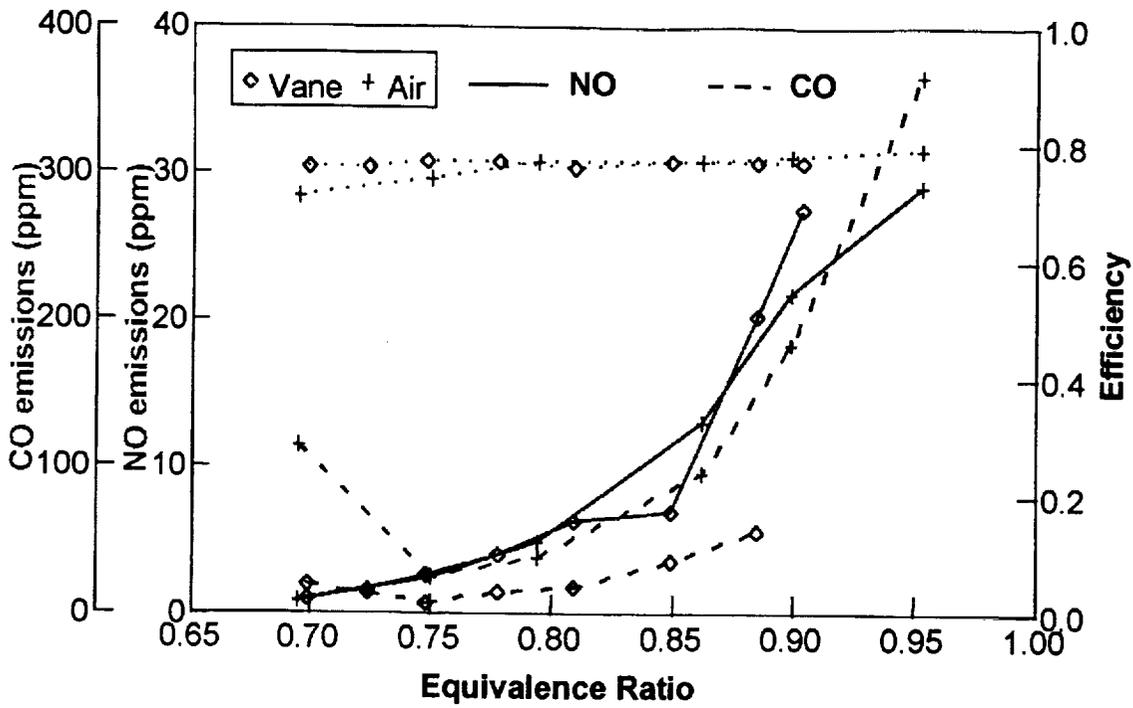


Figure 3 Comparison of the performances of air-jet and guide-vane LSBs fitted in a water heater simulator of 15 kW.

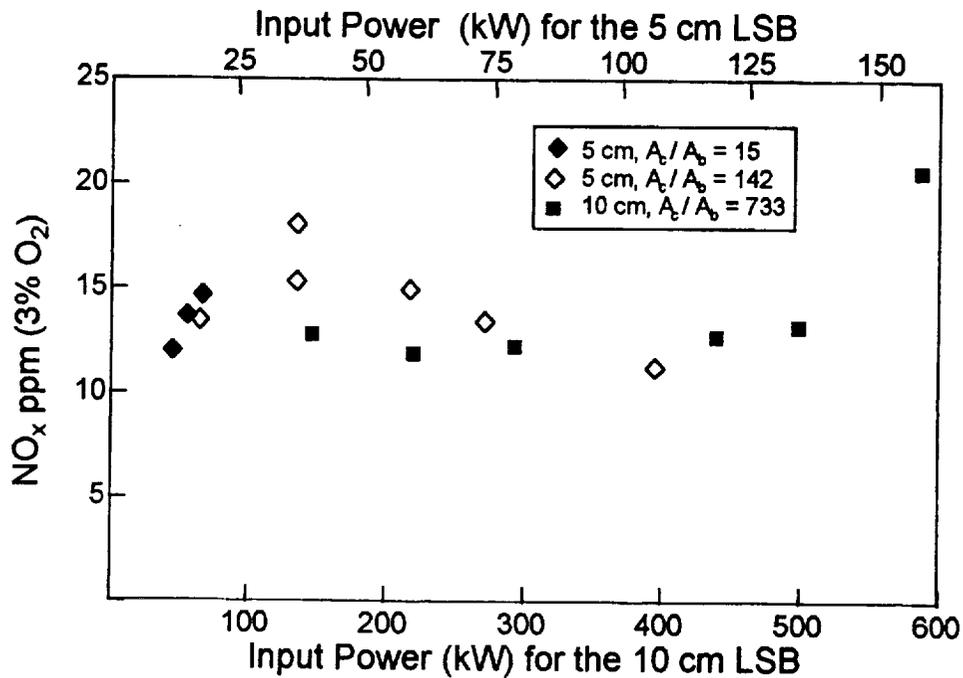


Figure 4: NO<sub>x</sub> emissions for three test configurations with  $\phi = 0.8$  (25% excess air).