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Development of a Low Swirl Injector Concept for Gas Turbines

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Abstract

This paper presents a demonstration of a novel lean premixed low-swirl injector (LSI) concept for ultra-low NO_x *gas turbines. Low-swirl flame stabilization method is a recent discovery that is being applied to atmospheric heating equipment. Low-swirl burners are simple and support ultra-lean premixed flames that are less susceptible to combustion instabilities than conventional high-swirl designs. As a first step towards transferring this method to turbines, an injector modeled after the design of atmospheric low-swirl burner has been tested up to T=646 F and 10 atm and shows good promise for future development.*

1. Introduction

Low emissions, lean-premixed combustion systems have been adopted by virtually every industrial gas turbine manufacturer to meet increasingly strict NO_x emissions regulations in the US and in many locations overseas. In general, the first generation lean premixed combustion engines are capable of < 25 ppm NO_x (15% O_2) on natural gas fuel. However, in many US regions manufacturers are facing a continuing trend to lower NO_x emissions to < 9 ppm (15% O_2). Therefore, the engines have to operate at ultra-lean premixed conditions that are more prone to unacceptably high combustion oscillations. These oscillations can lead to catastrophic turbine damage if not controlled and the problem has become a major barrier to reaching < 9 ppm NO_x. Substantial research and development have been devoted towards combustion on instabilities of lean premixed combustion, catalytic combustion, sensors for detecting instability, impact of alternate fuel on instability, and computational modeling of combustion processes. However, there have been relatively few investigations on novel non-catalytic lean premixed combustion concepts.

Since 1994, Lawrence Berkeley National Laboratory (LBNL) has been developing a low-emission lean-premixed combustion method that has been successfully demonstrated for industrial heating systems and is being commercialized for packaged boilers and industrial process burners. This new method exploits the propagating nature of lean

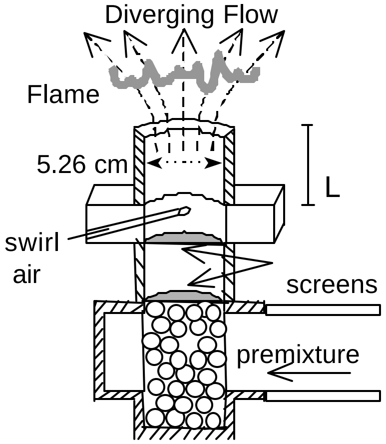

Figure 1 Schematics of a low-swirl burner with an air jet-swirler section

premixed turbulent flames by stabilizing them in divergent flows generated by low-swirl. The burner design is quite simple and the flame it generates can be oscillation free and less vulnerable to blow-off. The overall objective of this project is to develop a concept low swirl injector (LSI) suitable for further development for gas turbine applications.

2. Background of the technology

The concept of using low swirl to stabilize premixed turbulent flames was discovered in 1991 (Chan et al., 1992). The operating principle of the method is illustrated by Figure 1. This low-swirl burner (LSB) is the original version that uses inclined air-jets to impart swirl. It is essentially an open tube with four small tangential air jets [Yegian, 1998 #14]. Reactants at a given flow rate and ϕ are supplied through the bottom and interact with the swirling air. The swirl number of this jet-LSB is defined in the usual way by the ratio of the flowrates of the reactants and the swirl air (Claypole and Syred, 1980, Feikema et al., 1990)

$$S \equiv \frac{R_\theta R \pi}{A_\theta} \left(\frac{\dot{m}_\theta}{\dot{m}}\right)^2 \qquad (1)$$

Typically, jet-LSBs require $0.02 < S < 0.12$ to operate. This is almost an order of magnitude lower than the requirement $0.5 < S < 1$ for conventional high-swirl burners. At these low-swirl levels, the swirling motion is insufficient to cause vortex breakdown, a necessary precursor to flow recirculation. Instead, the flow stream diverges as it leaves the confines of the burner tube. The linear velocity decay region of this divergent flow is ideal for sustaining propagating premixed flames. The velocity “down-ramp” allows the flame to propagate from the downstream side and settle at the position where the local flow velocity is equal to the flame speed. The flame does not flash back because the velocity at the burner throat is higher than the flame speed. Neither does it flash back because the velocity downstream of the flame is lower than the flame speed.

Previous laboratory investigations (Cheng, 1995, Bedat and Cheng, 1995, Chan et al., 1992) have shown that flames generated by low-swirl burners have no recirculation zone. Their flowfields are also free of large velocity gradients in both the axial and radial directions. The flames remain very stable even under intense turbulence. Another interesting feature of these flames is that their flame speeds, S_T, measured by the axial velocity normal to the leading edge of the flame brush, scale linearly with turbulence intensity, u'. This characteristic is quite different than other premixed turbulent flame where S_T tends to level off at high u' (Bedat and Cheng, 1995).

To evaluate LSB feasibility for small heating appliances, the jet-LSB of Figure 1 was fitted in an 18 kW spa heater simulator (Yegian, 1998) and it adapted well to enclosures without generating flame oscillations or noise. The emissions of NO_x can be controlled to below 15 ppm (3% O_2) without significant effect on the thermal efficiency or CO emissions (< 50 ppm). In a more recent investigation, a larger 10.16 cm i.d. jet-LSB has been tested up to 2 MMBtu/hr and shows that the operating swirl number is a function of the swirler recess distance, L (Figure 1) (Yegian and Cheng, 1998).

3. Development of vane-swirler

The development of a vane-swirler is a critical step towards transferring LSB technology for practical use. This is because separate main and swirl controls needed for jet-LSBs are considered too complex. Because research on vane-swirlers has concentrated on high-swirl designs (Syred and Beer, 1974, Beer and Chigier, 1972, Lilley, 1977) very little was available on vane-swirler designs that generate the divergent flowfield needed for LSB operation. Extensive experimentation led us to the design shown in Figure 2 (Yegian and Cheng, 1996). The key feature that distinguishes this vane-swirler from a conventional swirler is that its centerbody allows a portion of the reactants to bypass the swirl annular. The novelty of our design (Cheng and Yegian, 1999) is the use of screens with different blockage ratios to balance the pressure drops across the bypass and the swirl vanes. These screens also help to maintain a uniform radial flow distribution and control turbulence level.

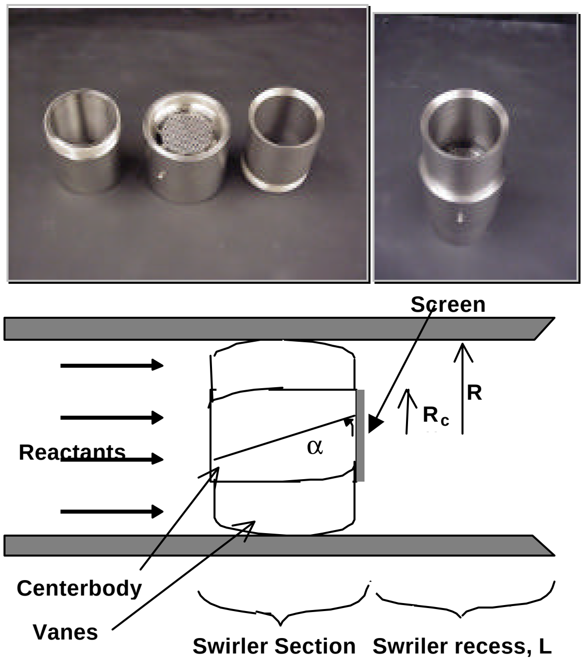

Figure 2 Vane-LSB and schematics of the swirler

For atmospheric applications, we tested a 52.6 mm i.d. LSBs with four screens made of perforated plates with blockage ratios of 65 to 75% (Yegian and Cheng, 1996). This LSB has a centerbody of R_c = 20.5 mm and 3.5 cm in length. It has eight straight vanes in angled at α = 37°. The swirler recess distance is L = 7 cm.

The vane-LSB design is also scalable. Our larger LSB is similar except for the vane angle α increased by a factor of 1.5 (7.68 cm i.d. and the ratio R_h/R = 0.776). This LSB was tested with aluminum foam as the screen material. It has an equivalent blockage ratio of about 80%. Test results performed in a boiler simulator at 300 kW is plotted in Figure 3 (From (Cheng, 2000)) and show that the LSB can achieve NO_x < 10 ppm and CO < 50 ppm (both at 3% O_2).

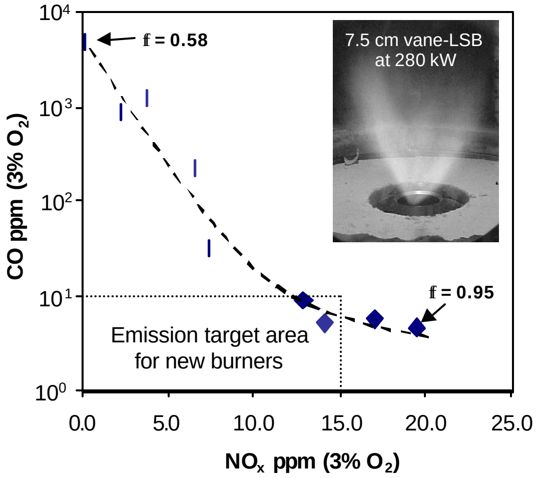

Figure 3 NO_x and CO emissions from a 7.5 cm vane-LSB at 210 < Q < 280 kW and 0.58 < ϕ < 0.95

More recently, the larger vane-LSB was tested up to 1 MW in a furnace simulator and the emissions of NO_x and CO were as low as 5 ppm and 20 ppm (both at 3%O_2) respectively. When this burner operates at 1 MW, the bulk blow velocity, U_o, is approximately 75 m/s. Testing of the smaller vane-LSB (5.26 cm i.d.) also shows that it is capable of operating up to 600 kW with $U_o \approx 90$ m/s. These results demonstrate that the low-swirl flame stabilization mechanism is valid at typical operating conditions of large combustion equipment. More importantly, they also show the vane-swirler design to be robust for atmospheric applications.

4. Validation of Flame Stabilization Mechanism at Turbine Conditions

In transferring this technology to turbine combustors, the critical task is to demonstrate the validity of the flame stabilization mechanism in preheated and pressurized environments and to determine swirl requirements. Towards this aim, a stainless steel 7.68 cm i.d. concept injector with jet-swirler was designed and built. This injector is essentially the same as the design shown in Figure 1. It is a 30 cm long open tube fitted with an air jet swirler at 10 cm upstream of the exit. The air swirler has four tangential small jets tilted 20^0 upstream. The jet swirler enables free adjustment of the swirl number. Four evenly distributed fuel rods are placed close to the air inlet end of the injector. Air split between the liner and the combustor is controlled by the use of different screens or perforated plates. Only one screen has been tested thus far.

The injector was fitted with a film-cooled liner and tested in a single injector test rig at Solar Turbines Incorporated. This facility is capable of supplying air to the test rigs at flow rates up to 4.1 kg/sec, pressures up to 2000 kPa, and temperatures up to 540C. Control and monitoring instrumentation are available for fuel and air flow rates, system pressures, temperatures, and to measure emissions of NO_x, CO, UHC, O_2, and CO_2. Combustion generated acoustics are monitored and quantified by a dedicated PC system. Combustion pressure can be controlled by an electronically actuated back pressure valve. A view port downstream of the combustor offers a view of the combustion process through a video monitor.

Successful firing of this prototype to 4.4 atm, 370 C with 0.45 kg air confirmed the validity of the flame stabilization mechanism at the lower end of turbine conditions. The range of operable swirl numbers ($0.08 < S < 0.7$) also suggests that the stabilization mechanism is robust and not highly sensitive to changes in pressures, initial temperature, flow and mixture conditions.

5. LSI Prototype with Vane-swirler

Test results of the jet-LSI strongly suggest that the vane-swirler design should also be operable under high inlet temperature and pressure. The vane-LSI concept prototype built for further testing is 7.62 cm i.d. and is comparable in size to current injectors in Solar's Centaur 50/Taurus 60 engines. It has a vane-swirler comprised of eight straight swirl vanes that are attached to the outer surface of the injector center body. The swirl vane angle is 37°. As mentioned above, the center body allows a portion of the flow to bypass the swirl vanes. To balance the flow split between the swirled and the nonswirled section, a perforated plate (screen) is attached at the exit plane of the center body. This screen acts as a flow straightener and enhances mixing. Several different screens were tested previously for an atmospheric boiler application and those results directed the selection of the screen used in the current test.

6. Defining Swirl Number of LSI

In deriving S for the vane swirler used in the prototype LSI, Eq. (1) does not apply. From the original definition based on the ratio of angular to axial flow momentum, S for the vane-swirler is:

$$S = \int_0^{R_i} UW r\,dr \Big/ R_i \left(\int_{R_c}^{R_i} U^2 r\,dr + \int_0^{R_c} U^2 r\,dr \right) \qquad (2)$$

here R_i and R_c are respectively the radii of the injector and the center body. Equation (2) can be further reduced to:

$$S = \frac{2}{3} \tan\alpha \frac{1 - (R_c/R_i)^3}{1 + (R_c/R_i)^2 \left((U_c/U_a)^2 - 1 \right)} \qquad (3)$$

U_c is the averaged axial velocity through the centerbocy, and U_a is the averaged axial velocity component in the outer annulus. U_c and U_a are not necessarily identical, as they are functions of the screen blockage.

For a fixed vane angle, α, functional dependence of S on U_c/U_a and R_c/R_i shows that it reduces to the proper physical limits. For $R_c \gg R_i$, S is zero, and for $U_c = 0$, S_v is identical to the definition of a hub swirler. Eq. (3) also shows that S can be varied by changing wither U_c/U_a *or* R_c/R_i.

Because Equation (3) is not very easy to apply as it requires velocity measurements, a more practical form would be to express it in terms ratio of mass fluxes through centerbody and annular (flow-split), $\dot{m}_c / \dot{m}_a = m$

$$S = \frac{2}{3} \tan\alpha \frac{1 - R^3}{1 - R^2 + [m^2 (1/R^2 - 1)^2] R^2} \qquad (4)$$

The other parameters are simply the vane angle, α, ratio of burner to center body radii $R_c/R_i = R$ and are the three parameters.

We found that the swirl number, S, together with the swirler recess distance, L determine the stable operating regime defined on a phase plane expressed in terms of fuel/air ratio and bulk flow velocity. For atmospheric applications, we found that the minimum value of S to be 0.4 and L/R_i can vary between 1 to 12. We also found that the type of screen, i.e. large holes versus small holes, can also have some effect on the lean blow-off.

As a necessary setup procedure of the rig-test, the effective flow areas of the LSI were measured. The effective flow areas of the center body and the swirl annular were also measured separately for the determination of the swirl number. With the use of the present 71% blockage screens, The effective flow areas (Aes) are as follows:

LSI [Full Open]	16 cm^2
Swirler	7.96 cm^2
Centerbody (71% screen)	8.09 cm^2

The flow split m is approximately 50/50 and the swirl number of the LSI prototype is about 0.435. A second screen was also cold flowed in the LSI. Of the two screens, the selected screen was chosen because it provided a slightly leaner primary zone than the other.

7. Set-up, Test Conditions and Procedures

The overall effective flow area of the LSI (16 cm^2) is most suitable for testing with a "film-cooled liner". This is the standard combustor configuration used for single injector high pressure testing at Solar Turbines. The liner is a can type combustor of 20.3 cm diameter and a length of 2.25D. It is constructed of 2 mm thick Hastelloy X sheet metal and film cooled. The LSI/Louvered Liner combination resulted in a combustion system alpha [% of total combustion system air in the primary zone] of 65%. A "Back Side Cooled" test combustor was also considered for evaluation with LSI. However, the effective flow area for the back-side-cooled liner indicated that it would produce a slightly richer primary zone compared to the film-cooled Liner.

As the purpose of these tests was to demonstrate the combustion concept, we did not elaborate on optimizing mixing. Four overlapping fuel injection spokes were positioned about 15 cm upstream of the swirler section. Each fuel tube has eleven equally spaced fuel injection ports and they are oriented to produce cross-flow injection (i.e., fuel port centerlines are 90° to the injector axis). The premixing length (the distance from the centerline of the downstream-most fuel tube to the exit plane of the injector) is approximately 3.4D. Three (3) thermocouples were fixed to the injector to monitor any significant flame shift or flashback precursors during the tests. Two were placed across each other on the outer wall of the injector barrel and the third was placed on the center body inner wall just upstream of the screen.

The tests were performed with natural gas. The test matrix is listed in Table I and comprises of four set points. These set points were designed to investigate LSI combustion performance at two combustor pressures (Sets 2 and 4) and to determine the performance at different injector flow velocities (Sets 1,2 and 3).

SET POINT	P [atm]	V_{inj} [m/s]	T_{in} [C]	W_{tot} [kg/s]	W_{inj} [kg/s]
1	5	23	220	0.59	0.36
2	5	30.5	220	0.77	0.5
3	5	38	220	0.952	0.59
4	10	30.5	341	1.22	0.77

Table 1 Test matrix

Within each set point, primary zone equivalence ratio, ϕ, was varied from 0.6 to 0.8 to provide a range of primary zone temperatures that encompass those in current low emission combustors (1300 to 1700C). The baseline condition in this test was Set 2 (P_{comb} = 5 atm / V_{inj} = 30.5 m/s). Set 4 (P_{comb} = 10 atm / V_{inj} = 30.5 m/s) was chosen to simulate combustor pressure of the Solar Centaur 50 engine so to compare LSI emissions and those from current low emissions engines.

Emissions and acoustics data were measured at each steady state test condition. In addition, at each set point fuel flow was gradually reduced (while all other parameters were held nearly constant) until lean blowout occurred. A minimum of two lean blowout points were taken at each set point; a third point was taken only if there was a significant difference in lean blowout air-fuel ratio between the first two points. A transient data file was recorded during each lean blowout point (1 second intervals) to accurately capture the conditions at extinction.

8. Results

Emissions

At the baseline condition (5 atm / 0.5 kg/s), the LSI prototype exhibited typical NO_x and CO trends with primary zone temperature, T_{pz}, (Figure 4). High CO was produced at T_{pzs} below ~ 1500C. NO_x remained below 100 ppm over the range of T_{pzs} at 5 atm and leveled off to less than 20 ppm. LSI emissions trends with T_{pz} at the other two flow rates also show typical asymptotic trends. However, at both the lower (0.36 kg/s) and higher (0.59 kg/s) flow rates, NO_x curves exhibit a linear characteristic at lower T_{pz}. This suggests that flow field stoichiometry was non-uniform (i.e., a non-homogeneous mixture) at these conditions. This is not surprising given the fact that the fuel spokes used for these rig-test had not been optimized to produce a uniform fuel injection rate per unit area and no provision was made to ensure that the flow rates to each of the four fuel spokes were balanced.

The different trends shown by the NO_x data at different flow rates strongly suggest that the LSI flame is multi-modal or that there is a locally optimal state (where mixing performance is "best") in this range of test conditions. The significant rise in CO that occurred at the higher injector flow rates suggests that the predominant source of CO oxidation quenching may have been injector air flow rather than combustor wall cooling effects. Typical premixed flame emissions trends with T_{pz} were also observed at 10 atm. Again, the more linear NO_x trend with T_{pz} indicates that poor mixing persisted.

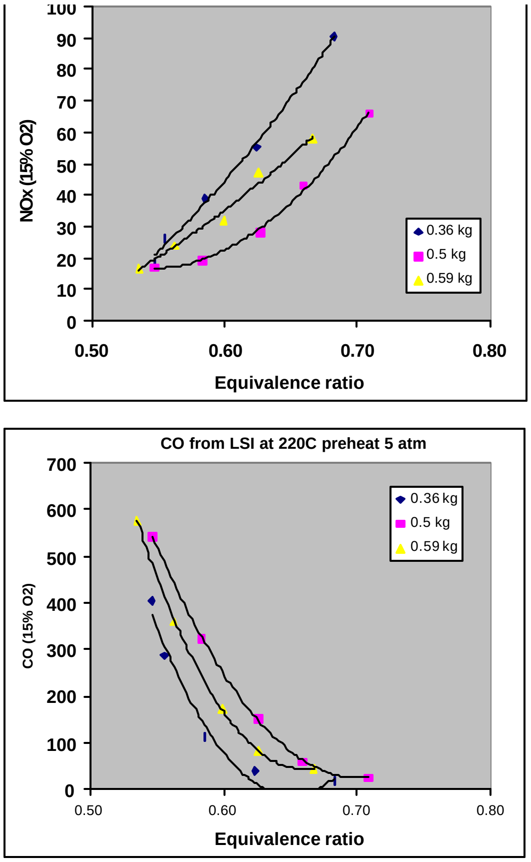

Figure 4 NO$_x$ and CO emissions of a LSI concept prototype

Comparing LSI emissions to those of the Centaur 50 design point (25/25 ppm NO$_x$ /CO, 1593 C T$_{pz}$, 10 atm) indicates that LSI CO performance is comparable to that of current low emissions engines. However, LSI NO$_x$ of 130 ppm at 1593C is much higher than Centaur 50 NO$_x$ and further substantiates that mixing performance is deficient with the current rig-test configuration.

Lean Blow-out

A distinctive feature of the LSI towards lean blow-out is that the flames did not exhibit the kind of pulsation typically found in conventional high-swirl injector towards LBO. The flames just became weaker with increased air-fuel ratio and disappeared. This seems to imply that LSI may be less susceptible to the combustion dynamics problems that affect current high-swirl injector. The LSI lean blowout trends are typical of other lean premixed injectors. For the 5 atm Sets 1,2, and 3, extinction decreased from air-fuel-ratio of 32 to 30.8 as injector flow velocity was increased. Comparing the Sets 2 and 4 with identical velocity at two different pressures, lean blowout occurred at leaner air fuel ratios (39.7) at the higher combustor pressure.

Acoustics

Excessive (audible) acoustic amplitudes were not observed with the LSI at any condition in the current rig test, The frequency peaks of the pressure spectra fall within a very narrow range from 208 to 228 Hz for the entire test matrix. Peak rms acoustics pressures were nominally 2.1 kPa for most of the 5 atm conditions and ranged from 2.1 to 4.8 kPa at 10 atm. These levels are comparable to a maximum allowable 3.4 kPa established for production hardware.

At 5 atm, acoustics energy did not change with equivalence ratio or with injector flow rate for Sets 1 and 3. For Set 2, 0.77 kg/s condition, there is a decrease in acoustics energy with increasing primary zone equivalence ratio. Recalling that Set 2 was the only one that appeared to have good mixing performance, the acoustics data also demonstrate that this Set seems to be optimal both in terms of NO$_x$ and acoustics performance. At the 10 atm conditions, acoustics energy was nominally twice as high as that at the 5 atm and peaked at ER$_{pz}$ = 0.50.

Flame shift and flash-back

There were no indications of significant flame shift or flashback events at any condition in the current tests. Outer barrel lip and center body lip temperatures were in the vicinity of combustor inlet air temperature throughout the tests that lasted for over seven hours. Outer barrel lip temperatures were at most 39 C higher than inlet air temperature and center body lip temperatures were nominally 22 C below inlet air temperature. Outer barrel lip temperature showed a slight decrease with increasing injector velocity. This seems to imply a slight downstream shift of the flame.

Summary

Rig tests at Solar Turbines Incorporated have demonstrated the low-swirl flame stabilization concept for gas turbine applications. It is well recognized that the development of lean premixed injector for gas turbines is non-trivial due to the dynamic nature of the combustion processes. Given the fact that the LSI prototype is essentially an atmospheric burner, successful completion of our test matrix indicates that we have indeed instigated a new and robust combustion concept for gas turbines. The use of a conventional combustor liner for these tests further illustrates that this technology can be engineered for integration into existing engines.

Test results obtained at typical gas turbine combustor inlet temperatures (220 and 341C) and pressures (5 and 10 atm) are very encouraging. Light-off of the LSI was easy and the flame remained very stable and free of high pressure fluctuations even towards lean blow-off. These test results show that much of the knowledge gained from LSB development can be transferable to LSI. These are our current conclusions:

1. The LSI demonstrated typical premixed flame emissions trends and lean blowout trends.
2. NO_x emissions are higher than those from low emissions engines due to poor mixing.
3. Combustion system acoustic amplitudes with the LSI remained inaudible and within or near the acceptable range at all operating conditions of the current test, including through all equivalence ratio transitions to lean blowout.
4. LSI flame stability was acceptable; there were no indications of significant flame shift or flashback in the current test.
5. The optimum conditions for this LSI prototype was found for 1.1 pps at 5 atm where NO_x and acoustic amplitude were minimal.

Acknowledgement

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References

Bedat, B. and Cheng, R. K. (1995) "Experimental study of premixed flames in intense isotropic turbulence," *Combustion and Flame,* **100,** 485-494.

Beer, J. M. and Chigier, N. A. (1972) *Combustion Aerodynamics,* Applied Science Publishers Ltd., London.

Chan, C. K., Lau, K. S., Chin, W. K. and Cheng, R. K. (1992) In *Twenty-fourth Symposium (International) on Combustion*The Combustion Institute, Sydney (Australia), pp. 519-525.

Cheng, R. K. (1995) "Velocity and scalar characteristics of premixed turbulent flames stabilized by weak swirl," *Combustion and Flame,* **101,** 1-14.

Cheng, R. K., Yegian, D. T., Miyasato, M. M., Samuelsen, G. S., Benson, C. E., Pellizzari, R., and Loftus, P. (2000) "Scaling and Development of Low-Swirl Burners for Low-Smission Furnaces and Boilers," *Trans Comb. Inst.,* **28**.

Cheng, R. K. and Yegian, D. T. (1999) "Mechanical Swirler for a Low-NOx Weak-Swirl Burner," *USA Patent No. 5,879,148,* March 9.

Claypole, T. C. and Syred, N. (1980) In *Eighteenth Symposium (International) on Combustion*The Combustion Institute, Waterloo, Canada, pp. 81-89.

Feikema, D., Chen, R. H. and Driscoll, J. F. (1990) "Enhancement of flame blowout limits by the use of swirl," *Combustion and Flame,* **80,** 183-195.

Lilley, D. G. (1977) "Swirl flows in combustion : a review," *AIAA Journal,* **15,** 1063-1078.

Syred, N. and Beer, J. M. (1974) "Combustion in swirling flows: a review," *Combustion and Flame,* **23,** 143-201.

Yegian, D. T. and Cheng, R. K. (1996) "Development of a vane-swirler for use in a low NO_X weak-swirl burner," in *American Flame Research Committee International Symposium,*

Yegian, D. T. and Cheng, R. K. (1998) "Scaling the Low Swirl Burner from 15kW to 600kW," in *American Japanese Flame Research Committee International Symposium,*

Yegian, D. T. a. C., R.K. (1998) "Development of a Lean Premixed Low Swirl Burner for Low NOx Practical Applications," *Combustion Science and Technology,* **139,** 207-227.