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Journal

Symposium (International) on Combustion, 21(1)

ISSN

0082-0784

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Publication Date

1988

DOI

10.1016/S0082-0784(88)80378-3

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THE EFFECT OF INLET CONDITIONS ON THE PERFORMANCE AND FLOWFIELD STRUCTURE OF A NON-PREMIXED SWIRL-STABILIZED DISTRIBUTED REACTION

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A model reactor is used to investigate the extent to which the overall performance and detailed flowfield structure of a non-premixed swirl-stabilized distributed reaction are sensitive to modest changes in inlet conditions (e.g., fuel injection angle, inlet geometry, and swirl vane solidity). Measurements of combustor performance are based on exhaust plane species concentration profiles (HC, CO₂, CO, O₂), combustion efficiency, and visual observation of combustor stability. The detailed flowfield structure is established by spatially mapping the axial and azimuthal velocity fields using two-component laser anemometry, and the temperature field using a thermocouple probe. The results show that relatively modest changes in inlet conditions can dramatically affect the flowfield structure. As an example, for the model reactor evaluated the addition of a small step at the outer boundary of the swirler yields significantly lower centerline axial velocities and a more uniform thermal structure in the recirculation zone. Furthermore, a modest reduction in swirl vane solidity transforms the aerodynamic structure of the recirculation zone from an off-axis to a central, on-axis structure. These results explain, in part, the contradictory conclusions drawn from data acquired in non-premixed swirl-stabilized distributed reactions, and establish that comparisons and generalizations of such flows require, at a minimum, (1) careful measurements and specification of the inlet conditions, (2) detailed measurements of the flow structure, and (3) an assessment of the effects of modest changes in key operating and configurational variables.

Introduction

Non-premixed swirling flows are found in many combustion systems, notably, gas turbines, boilers, furnaces, and incinerators. If the mixing induced by the swirl is weak, the system behaves as a diffusion flame. As the mixing increases, the flame front becomes diffuse, dividing first into a distribution of flamelets and finally into a spatially-distributed reaction. In the limit of perfect mixing, the spatially-distributed reaction is uniformly mixed. Reactions in combustion systems that are spatially distributed are classified here, for convenience, as "distributed reactions".

Examples of measurements in distributed reactions include both model furnaces (e.g., Reference 1) and model gas turbine combustors (e.g., Reference 2). The conclusions drawn from studies conducted in such systems are regularly contradictory and suggest that the inlet conditions (i.e., inlet flow conditions and inlet reactor geometry) dictate the combustor

performance and structure of the flowfield. The questions raised include:

- Are the performance (e.g., combustion efficiency, stability) and the flowfield structure (e.g., aerodynamic field, thermal field) sensitive to relatively modest changes in the inlet conditions?
- Are data acquired and conclusions drawn with respect to non-premixed swirl-stabilized distributed reactions inlet condition specific, precluding generalized interpretation?

This paper reports on a parametric study undertaken to explore these questions in the model reactor presented in Fig. 1. The inlet condition parameters considered include fuel loading, fuel injection angle, fuel injection velocity, radial location of fuel injection, swirl-to-dilution air flow ratio, inlet geometry, and swirl vane solidity. For brevity, results are reported in the present paper for fuel injection angle, inlet geometry, and swirl vane solidity.

Background

Overview

Non-premixed distributed reactions can be stabilized by physical bodies such as unshrouded⁴ or shrouded⁵ disks, and step expansions,⁶ and aerodynamically by swirl,² swirl and wall-jets,⁷ and combinations of swirl, wall-jets, and step expansions.^{1,8} In all cases, a recirculation zone is established within which products and intermediates are backmixed to combine with and ignite the incoming reactants. Attention in the present study is directed to distributed reactions that are swirl-stabilized.

Studies undertaken to characterize and understand the effect of swirl on combustion performance and flowfield structure have utilized a variety of methods of making velocity field measurements - physical probes, such as pitot probes and hot-wire anemometers⁹⁻¹¹ and, more recently, laser diagnostics such as laser anemometry.¹²⁻¹⁴ To date, temperature measurements have been made principally with thermocouples,^{2,14} but examples using laser diagnostics are beginning to appear.¹⁵ Flow visualization techniques such as neutrally buoyant helium bubbles,³ smoke-wires,¹¹ and high-speed cinematography³ have also been used to document the turbulence structure and flow dynamics of swirling flows. The parameters investigated typically include the effect of reaction and swirl strength, and results are commonly presented in terms of mean flowfield properties (i.e., velocity and temperature profiles). However, select studies have considered more detailed structure including turbulence intensity, kinetic energy, Reynolds stress, and heat flux.^{1,2,3}

Due to the complexity of swirl-stabilized distributed reactions, conclusions drawn from one study regularly contradict those of others. As to whether reaction affects the shape and form of the recirculation zone, results have shown both a lengthening,¹ and no change³ in the size of the recirculation zone. With respect to isotropy, the flowfield has been found to be either isotropic^{3,16} or anisotropic¹ under isothermal conditions. Similar conflicts are reported for reacting conditions.^{1,3} The effect of increasing swirl number is also mixed, varying from a slight increase in the length of the recirculation zone¹⁷ to a substantial increase.⁹

The dichotomy of these results suggests that the performance and flowfield structure of swirl-stabilized distributed reactions are at least dictated by the inlet conditions and, in all probability, are also sensitive to relatively modest changes in inlet conditions.

Present Study

The present study addresses the sensitivity of combustion performance and flowfield structure to relatively modest changes in select inlet conditions. The objective is to systematically vary parameters associated with key inlet conditions, and document the extent to which the parametric variation affects combustion performance and the aerodynamic and thermal structure of a particular model laboratory reactor. Measurements of combustor performance are based on exhaust plane species concentration profiles (HC, CO₂, CO, O₂), combustion efficiency, and visual observation of combustor stability. The detailed flowfield structure is established by spatially mapping the axial and azimuthal velocity fields using two-component laser anemometry, and the temperature field using a thermocouple probe. The overall goals are to provide guidance for assessing data from combustion systems with swirl-stabilized distributed reactions, and to assess how (if at all) such data can be generalized.

Experiment

Reactor

The model turbulent reactor, presented in Fig. 1 and described in detail elsewhere,^{2,3} consists of an 80 mm I.D. cylindrical stainless steel tube that extends 32 cm from the inlet plane of the reactor. Flat optical windows (25 mm × 306 mm) are mounted perpendicular to the horizontal plane on both sides to provide clear, optical access for two-component laser anemometry measurements. For flow visualization, the stainless steel tube is replaced with a Kimble glass tube.

Swirl vanes (57 mm O.D.) are concentrically located within the tube around a 19 mm O.D.

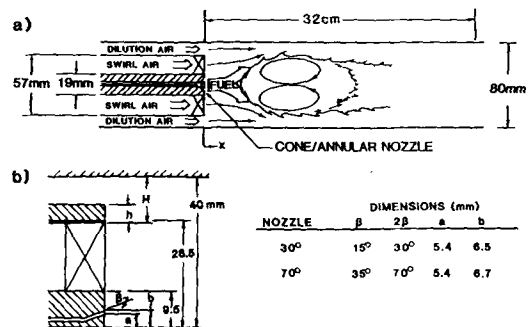


FIG. 1. Model Laboratory Reactor. a) Reactor; b) Geometrical Details.

centrally positioned fuel delivery tube. The vanes impart an angle of turn to the flow, 60° in the present study, with an option for either 70% or 100% solidity (the percentage of blockage or “see-through” area of the swirler passage). Two inlet plane configurations, obtained by changing the step height (h/H), are accommodated (Fig. 1b).

Fuel (propane) is introduced through a cone annular nozzle at the end of the central fuel delivery tube. For the present paper, results for two angles of injection (70° and 30° full angle) are reported. Geometrical details are provided in Fig. 1b. The two nozzles have an identical inner radius of injection while the outer radius (“b”, Fig. 1b) is specified to yield an identical fuel injection velocity.

Laser Anemometry

The aerodynamic field is established using the two-color laser anemometry (LA) system described previously.^{2,3} Axial and azimuthal velocity measurements are acquired at eight axial locations, from 0.5 cm to 24.0 cm downstream of the nozzle (0.06 to 3.0 duct diameters), and at 10 uniformly spaced radial locations from the centerline to the outer wall.

Temperature

The thermal field is established using a Type R thermocouple probe mounted on a three-axis positioning traverse.¹⁸ Mean temperature measurements are acquired at the same axial and radial positions as the velocity measurements. The data are presented, uncorrected for radiation loss, as two-dimensional fields created using the post processing capability of PATRAN-G (PDA Engineering), a computer-aided engineering software package.

Species Concentration

Combustion gases are sampled and analyzed for O_2 , CO_2 , CO and hydrocarbons using a sample probe and a continuous gas analysis system described elsewhere.¹⁹ Species concentration data are taken at the last measurement plane (24.0 cm) in the far wake of the recirculation zone and at five uniformly spaced radial positions from centerline to the outer wall.

Results and Discussion

The results section begins with a description of the basic aerodynamic and thermal structure for the reactor using a baseline operating and

configurational condition as the example. Next, results are presented for parametric variations on fuel injector angle, inlet geometry, and swirl vane solidity. The test conditions, including the values of the parameters, are presented in Table I. For all conditions reported, the reactor operates in a steady-state mode with small spatial excursions ($\pm 10\%$) of the recirculation zone length on the order of 100Hz.³ Tabulated data sets are available.²⁰

Basic Flowfield Structure

The basic aerodynamic flow structure of the reactor is presented in Fig. 2a for an arbitrarily selected baseline case (Table I: 70° Nozzle, $h/H = 0.08$, 100% Solidity). Axial radial profiles are shown on the top half of the upper figure, while azimuthal profiles appear on the bottom. (For clarity, only select profiles are presented.) Also shown is the centerline profile of the axial velocity.

TABLE I
Parameters

Parameters	Baseline	Parametric Variation
Reference Velocity (m/s)	7.5	—
Overall Equivalence Ratio (ϕ)	0.3	—
Swirl-to-Dilution Air Flow Ratio	1.0	—
Pressure (atm)	1.0	—
Fuel Injection Angle ($^\circ$) ^a	70	30
Inlet Geometry (h/H) ^a	0.08	0.67
Swirl Vane Solidity (%)	100	70

a. See Fig. 1b for definition

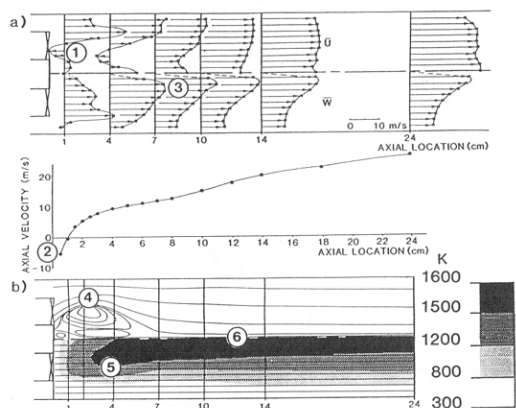


FIG. 2. Basic Aerodynamic and Thermal Structure (Baseline: 70° Nozzle, 100% Solidity, $h/H = 0.08$). a) Velocity Profiles; b) Streamlines and Temperature.

Examination of the radial profiles of axial velocity at the 1 cm and 4 cm stations shows that a strong zone of recirculation is formed off-axis ①.* Examination of the centerline profile of axial velocity reveals a small recirculation zone, as well, within the hollow cone of the fuel injector ②. However, centerline axial velocities are generally positive reflecting the diversion of a portion of the fuel jet to the centerline for this set of inlet conditions.

The mean azimuthal velocity peak moves inward at downstream locations ③ as a result of 1) the mixing and dilution of the swirl velocity with the dilution stream, 2) the swirling inlet air that flows initially out and around the recirculation zone and then collapses toward the centerline downstream, and 3) conservation of angular momentum in the radially inward flow.

Lines of constant stream function (Fig. 2b), obtained by radially integrating the profiles of mean axial velocity,³ illustrate the form of the "time-averaged" flowfield and clearly delineate the length and radial extent of the recirculation zone ④. Further evidence of off-axis recirculation is given by the mean thermal field where the peak temperatures coincide spatially with the recirculation zone ⑤. Downstream of the recirculation zone, the temperatures peak at the centerline within a spiralling core which extends to the exit of the combustor ⑥.

The concentration profiles (not presented for brevity) reflect the wake region temperature data with the CO₂ concentrations highest on the centerline and the hydrocarbon and O₂ concentrations increasing radially outward from the centerline. In the wall region where the flow is dominated by the cool dilution air, the hydrocarbon concentrations are slightly elevated and the CO₂ concentrations are at a minimum. These results suggest that a portion of the fuel is transported to and quenched in the wall region.

Due to the large cross-sectional area represented by the outer flow region, the combustion efficiency is sensitive to and limited by the value of the hydrocarbon concentration at the wall. As a result, combustion efficiencies do not exceed 94% and, for the parametric analyses conducted in the present study, do not fall below 84%. The highest combustion efficiency (93.6%) occurs for the baseline condition.

Changes to the inlet conditions that affect the partitioning of fuel likely control the combustor performance and structure of the flow. The

parameters selected for variation in the present study are based on the extent to which each is likely to influence the mixing of fuel and air.

Parametric Variation

Fuel Nozzle Angle. A decrease in fuel nozzle angle to 30° yields the same general structure of the velocity field as that of the baseline condition. However, one notable exception occurs for the 30° nozzle. The centerline axial velocity is higher immediately downstream of the nozzle (Fig. 3a) reflecting the transport of more fuel along the centerline than in the case of the 70° nozzle ①.

The general structure of the temperature field is also similar for both nozzle angles with two notable exceptions (Fig. 3b). First, the temperatures in the recirculation zone for the 30° nozzle are noticeably lower reflecting a zone of lower stoichiometry ②. Second, the centerline temperature is suppressed near the nozzle, corresponding to a fuel enriched core ③. As a result, the centerline values of carbon dioxide are lower and the carbon monoxide values are higher for the 30° nozzle. Not only is the combustion more complete along the centerline of the reactor for the 70° nozzle, but the hydrocarbon concentration in the wall region is substantially lower. The latter result is attributed to the more complete oxidation of the fuel processed through the recirculation zone. Hence, the combustion efficiency for the 70° nozzle is significantly higher (the highest for the conditions evaluated) than that of the 30° nozzle (the lowest for the conditions evaluated).

Inlet Geometry. The centerline axial velocity and temperature profiles for the change in inlet geometry are presented in Figure 4. This

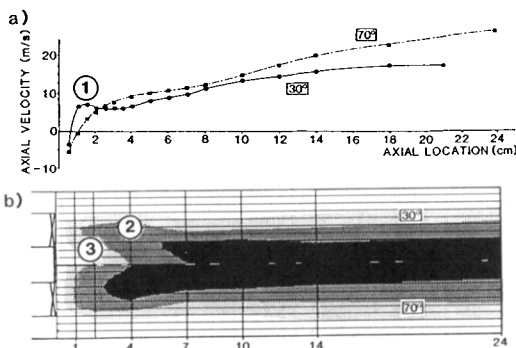


FIG. 3. Nozzle Injection Angle ($2\beta = 30^\circ, 70^\circ$; 100% Solidity, $h/H = 0.08$). a) Centerline Velocity Profile; b) Temperature.

*Circled numbers refer to circled locator points in the figure.

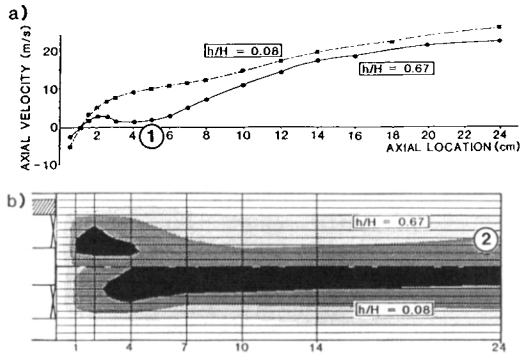


FIG. 4. Inlet Configuration Change ($h/H = 0.08$, 0.67 ; 70° Nozzle, 100% Solidity).
a) Centerline Velocity Profile; b) Temperature.

modest geometrical change produces a significant effect on both the aerodynamic and thermal fields. First, the centerline axial velocities (Fig. 4a) are substantially lower with the inlet geometry change ①, indicating that the centerline penetration of fuel is suppressed. Second, the temperature field for this case (Fig. 4b) shows that the temperatures are more uniform within the recirculation zone than for the baseline condition. As a result, the uniformity of temperature at the exhaust plane is improved with the geometry change ②. This is a direct result of the retention and more effective processing of fuel within the recirculation zone. The combustion efficiency for this condition (90.1%) is comparable to, but lower than, that of the baseline case (93.6%)

For the 30° nozzle, a change in the inlet geometry also results in lower centerline velocities. The change is less dramatic, however, than that observed for the 70° nozzle.

Swirl Vane Solidity. Figure 5 presents the velocity data documenting the effect of a change in swirl vane solidity. Reducing the swirl vane solidity from 100% to 70% dramatically affects the aerodynamic structure of the flowfield. First, a long on-axis recirculation zone is induced which extends from the nozzle face to 6 cm downstream of the inlet plane ①. Second, the azimuthal velocities are significantly lower throughout the flowfield ②. The thermal field (not shown due to space limitations) is changed as well in the recirculation region where the temperatures are much lower with the reduced solidity vanes. These dramatic differences in the "dome" region notwithstanding, the temperature profiles are similar in the wake of the recirculation zone, and the combustion efficiency is slightly lower for the 70% solidity vanes (92.1% compared to 93.6% for the

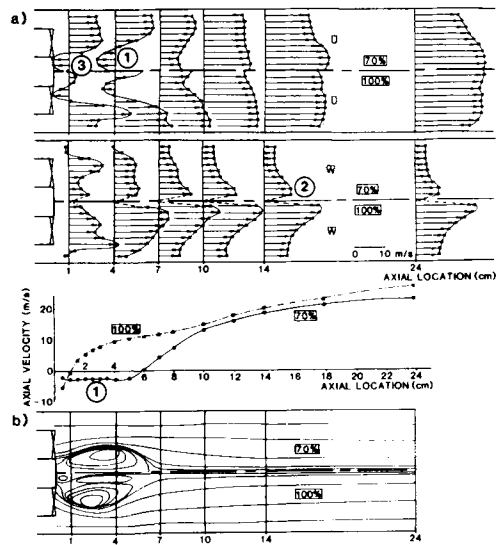


FIG. 5. Solidity Change (70%, 100% Solidity; 70° Nozzle, $h/H = 0.08$).
a) Velocity Profiles; b) Streamlines.

baseline case). Similar effects are observed with the 30° nozzle and 70% vanes

The generation of an on-axis recirculation by a reduction in swirl vane solidity does not agree with intuition. A reduced solidity should translate into a reduced swirl number and, hence, a reduced potential for inducing on-axis recirculation. An explanation in the present case for this apparent dichotomy is found in the axial velocity profile at 1 cm (Fig. 5a) ③. Note the high value of axial velocity immediately downstream of the swirler inner radius. (This is the location within the swirler where the "see-through" area is a maximum.) This high axial velocity stream (note the relatively low azimuthal velocity associated with this stream) creates a recirculation in the dump plane of the fuel delivery tube. Hence, the performance and flowfield structure of the reactor in this case are dominated not by the swirl, but by a bluff body stabilized recirculation.

Conclusions

An investigation into the effects of inlet conditions on the overall performance and detailed flowfield structure of a model reactor was conducted. Parameters included fuel injection angle, swirl vane solidity, and inlet geometry. A step added at the inlet plane effectively increased the area into which the swirling air could expand, and resulted in lower centerline axial velocities and a significantly transformed

thermal field. A dramatic effect also resulted from a decrease in the solidity of the swirl vanes where the recirculation was transformed from an off-axis to an on-axis structure, and the mode of stabilization was transformed from a swirl induced to a bluff body induced recirculation. The following conclusions are drawn from the present study:

1. The performance and flowfield structure of swirl-stabilized distributed reactions are sensitive to relatively modest changes in inlet flow conditions and reactor configuration.

2. Use of data acquired from such devices requires, at a minimum, a careful and detailed delineation of inlet flow conditions and reactor geometry.

3. To compare data from such systems and formulate generalizations on swirl-stabilized distributed reactions, the data should include detailed measurements of the flowfield structure and a sensitivity analysis of key operating and configurational variables, such as: fuel injection specifications, method of swirl production, and inlet reactor geometry.

Acknowledgements

The efforts of (i) Masanao Yanigihara in the collection of data for the scoping analysis during a residence leave from the Osaka Gas Company, (ii) Jack Brouwer for the collection and plotting of detailed laser anemometry and temperature data, (iii) Jim White, Jim Cox, and Lou Crain of PDA Engineering for their support in applying PATRAN-G to the temperature data, and (iv) Janice Johnson in the preparation of the manuscript are gratefully acknowledged.

REFERENCES

1. BAKER, R.J., HUTCHINSON, O., KHALIL, E.E., AND WHITELAW, J.H.: *Fifteenth Symposium (International) on Combustion*, p. 553, The Combustion Institute, 1974.
2. LARUE, J.C., SEILER, E.T., AND SAMUELSEN, G.S.: *Twentieth Symposium (International) on Combustion*, p. 277, The Combustion Institute, 1984.
3. BRUM, R.D., AND SAMUELSEN, G.S.: *Exp. Fluids*, 5, 95 (1987).
4. LEONARD, P.A., AND MELLOR, A.M.: *Combust. Flame*, 42, 93 (1981).
5. SWITZER, G.L., GOSS, L.P., TRUMP, D.D., REEVES, L.M., STUTRUD, J.S., BRADLEY, R.P., AND ROQUEMORE, W.M.: CARS Measurements in the Near Wake Region of an Axisymmetric Bluff Body Combustor, AIAA-85-1106, 1985. Accepted AIAA Journal (in press).
6. SMITH, G.D., GIEL, T.V., AND CATALANO, C.G.: *AIAA J.*, 21, 270 (1983).
7. FERRELL, G.B., AOKI, K., AND LILLEY, D.G.: Flow Visualization of Lateral Jet Injection into Swirling Crossflow, AIAA-85-0059, 1985.
8. RUDOFF, R.C., AND SAMUELSEN, G.S.: Detailed Measurements of Velocity, Temperature, and Soot In a Model Gas Turbine Combustor with Wall Injection, AIAA Paper 86-0523, 1986.
9. CHIGIER, N.A., AND BEER, J.M.: *J. Basic Eng.*, 4, 788 (1964).
10. SYRED, N., CHIGIER, N.A., AND BEER, J.M.: *Thirteenth Symposium (International) on Combustion*, p. 587, The Combustion Institute, 1971.
11. RHODE, D.L., LILLEY, D.G., AND McLAUGHLIN, D.K.: *AIAA J.*, 21, 593 (1983).
12. CHIGIER, N.A., AND DVORAK, K.: *Fifteenth Symposium (International) on Combustion*, p. 573, The Combustion Institute, 1974.
13. GOULDIN, F.C., DEPSKY, J.S., AND LEE, S.L.: *AIAA J.*, 23, 95 (1985).
14. HEITOR, M.V., TAYLOR, A.M.K.P., AND WHITE-LAW, J.H.: *Exp. Fluids*, 3, 323 (1985).
15. GOULDIN, F.C., AND HALTHORE, R.N.: *AIAA J.*, 24, 1129 (1986).
16. SO, R.M.C., AHMED, S.A., AND MONGIA, H.C.: *Exp. Fluids*, 3, 221 (1985).
17. OWEN, F.K.: *AIAA J.*, 14, 1556 (1976).
18. SMITH, R.A., WOOD, C.P., AND SAMUELSEN, G.S.: Formation of Soot from Practical and Surrogate Fuels in a Swirl-Stabilized Atomized Combustor, AIAA-85-1311, 1985.
19. McDANNEL, M.D., PETERSON, P.R., AND SAMUELSEN, G.S.: *Combust. Sci. Tech.*, 28, 211 (1982).
20. CHARLES, R.E., AND SAMUELSEN, G.S.: Detailed Data Set: Velocity (\bar{u} , \bar{w} ; u' , w') and Temperature (\bar{T}) Measurements in the Dilute Swirl Combustor (DSC) for a Parametric Variation in Inlet Conditions, Report ARTR-85-9, UCI Combustion Laboratory, University of California, Irvine, 92717, 1985.

COMMENTS

J. Swithenbank, Sheffield University, UK. It would appear your swirl vanes are partially stalled, especially at low blockage. Did you measure the swirler pressure drop for each configuration and if so, how did they compare?

Author's Reply. A flat-vane swirler was selected to represent designs preferred in practical applications.¹ As a result, both the 70% and 100% vanes likely perform under stalled conditions. For the operating conditions reported ($V_{ref} = 7.5$ m/s, swirl-to-dilution

air ratio, $S/D = 50/50$), the swirler pressure drops are 30.7 mm H₂O and 169.4 mm H₂O for the 70% and 100% vanes, respectively.

REFERENCE

1. LEFEBVRE, A.: Gas Turbine Combustion, p. 135, McGraw-Hill, 1983.

Karim A. Hirji, Imperial College, England. Since one of your objectives was to compare your results with those reported in the literature and to identify inlet parameters which influence the structure of swirl-stabilized flow, could you please comment why "swirl solidity" rather than swirl number (used extensively in the past and present literature) has been employed to relate your results? Could you please explain the reason for your choice for the type of swirl generator employed? Please confirm if fully turbulent inlet Reynolds numbers were used throughout the study?

Author's Reply. A comparison of our results with previous studies was not the intent of the present study. Those conducting experimental and modeling studies of elliptic flows have recognized and reported the likely dependence of flowfield structure on inlet conditions. However, results to date are typically reported for one configuration and, at the most, a few disparate operating conditions. Studies reported in the literature have not included sensitivity analyses of flowfield structure to inlet conditions. Hence, rather than comparing our results, our goals were to document the importance of a sensitivity analysis, and to ascertain whether sensitivity analyses are necessary (1) to interpret the results (as the example with the 70% solidity vanes demonstrate), (2) to generalize the results, and (3) to remove the apparent contradictions in conclusions that are regularly reported for swirling flows.

The swirl numbers for the vanes employed in this study are 0.82 for the 70% vanes and 1.27 for the 100% vanes when integrated across the swirl vanes. Although the lower swirl number (associated with lower solidity vanes) suggests a lower tendency toward on-axis recirculation, just the opposite occurs. The swirl number is therefore misleading in the present case and does not explain the observed differences in flowfield structure with the two vanes. Instead, it is the distribution of blocked area that results in the transformation from an off-axis, swirl-stabilized reaction (baseline condition, 100% vanes) to an on-axis, bluff-body stabilized reaction (70% vanes). The flowfield structure is thus governed, in this case, by the distribution of the blocked area in the swirler and not by the swirl number.

With respect to the swirl generator type, the swirl

generators were designed to represent practical combustor vanes with the added features of thin blades to minimize wake effects.

The duct "Reynolds number" is $\sim 38,000$ based on the bulk cold flow (reference) velocity and duct diameter. Evidence that the inlet flow is "fully turbulent" is the insensitivity of the recirculation zone geometry to changes in reference velocity.

Wolfgang Leuckel, Universität Karlsruhe, West Germany. Apart from the fuel injection angle, fuel injection velocity or momentum is an important parameter for mixing and ignition stability in swirl-stabilized flames. Has the fuel momentum been varied and, if so, which range of fuel exit velocity has been covered?

Author's Reply. The evaluation of fuel injection momentum was limited to one test with the 100% solidity vanes. A 70° nozzle was constructed with the same inner radius (a, Fig. 1) but twice the area of the baseline 70° nozzle. Hence, for a fixed fuel mass flow rate, the averaged injection velocity was 50% less than the baseline value of 12.2 m/s. No significant differences between the two nozzles were observed in the axial and azimuthal velocity profiles. The two-dimensional mean temperature field yielded a small difference, with the high temperature region in the recirculation zone slightly larger for the lower velocity nozzle. Hence, the fuel jet momentum did not play a significant role in determining the flowfield structure for the operating conditions considered. In follow-up work, the velocity will be increased to 200% of the baseline velocity with the same mass flow rate. A more significant effect is expected to result from this variation.

N. Shah, Rolls Royce, UK. What were the effects on efficiency?

Author's Reply. The baseline condition (70° nozzle, 100% vanes, $\phi = 0.3$, $h/H = 0.08$) yielded the highest combustion efficiency (93.6%). The lowest efficiency (84.5%) occurred for the 30° nozzle (100% vanes, $\phi = 0.3$, $h/H = 0.08$). The efficiencies for the remaining two conditions varied only slightly from the baseline with 92.1% for the inlet geometry change (70° nozzle, 100% vanes, $\phi = 0.3$, $h/H = 0.67$), and 90.1% for the 70% solidity swirl vanes (70° nozzle, $\phi = 0.3$, $h/H = 0.08$). A full complement of exhaust species concentration profiles are available.¹

REFERENCE

1. Reference 20 in text.