3.2.1.3

Rich Burn, Quick-Mix, Lean Burn (RQL) Combustor

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3.2.1.3-1 Introduction

The Rich-Burn, Quick-Mix, Lean-Burn (RQL) combustor concept was introduced in 1980 as strategy to reduce oxides of nitrogen (NO_x) emission from gas turbine engines.[1] Later, in the 1990's, the concept was targeted by the National Aeronautics and Space Administration (NASA) for the reduction of nitrogen oxides in next generation aero-propulsion engines. Today, the RQL is the anchor combustor technology in aeroengines deployed commercially by Pratt & Whitney under the name TALON (Technology for Advanced Low NO_x). Due to safety considerations and overall performance (e.g., stability) throughout the duty cycle, the RQL is preferred over lean premixed options in aeroengine applications.

In stationary applications, lean premixed combustor technology is the standard. Safety considerations are not as severe, the duty cycle is more constrained, and the reduction in NO_x emission is more substantial in contrast to RQL technology. However, RQL combustor technology is of growing interest for stationary applications due to the attributes of (1) more effectively processing fuels of complex composition, and (2) processing fuels of varying composition. The latter is becoming of importance with the increasing international competition for fuels in general, the burgeoning interest in biomass fuels, the expanding use of "opportunity fuels" (land-fill gases, digester gases, well-head gases), and the growing use of liquefied natural gas to either complement domestic sources or serve as the sole source of natural gas to a large region of a country or the country as a whole. The California Energy Commission is engaged in RQL technology research, in cooperation with the U.S. Department of Energy, to explore the utility of RQL strategies as an alternative to combustors for niche applications in the stationary production of electrical power.

The RQL concept is predicated on the premise that the primary zone of a gas turbine combustor operates most effectively with rich mixture ratios (Figure 1). First, a "rich-burn" condition in the primary zone (e.g., $\Phi = 1.8$) enhances the stability of the combustion reaction by producing and sustaining a high concentration of energetic hydrogen and hydrocarbon radical species. Secondly, rich burn conditions minimize the production of nitrogen oxides due to the relative low temperatures and low population of oxygen containing intermediate species (Figure 2).

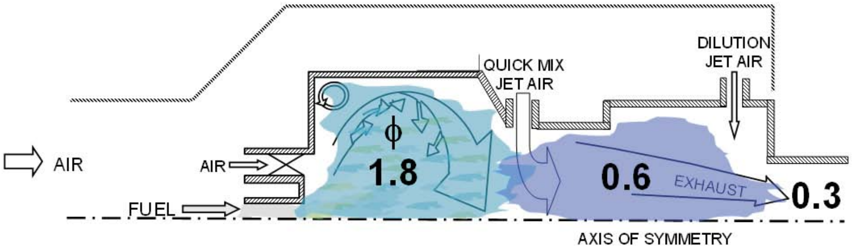


Fig. 1. Rich-Burn, Quick-Mix, Lean-Burn Combustor (Φ, Equivalence Ratio)

The effluent emanating from the rich primary zone will be high in the concentration of partially oxidized and partially pyrolized hydrocarbon species, hydrogen, and carbon monoxide. As a result, the effluent cannot be exhausted without further processing. In particular, the addition of oxygen is needed to oxidize the high concentrations of carbon monoxide, hydrogen, hydrocarbon intermediates. This is accomplished by injecting a substantial amount of air through wall jets to mix with the primary zone effluent and create a "lean-burn" condition prior to the exit plane of the combustor. Ideally, this will result in the emission of an effluent comprised of the major products of combustion (CO_2, H_2O, N_2, O_2) and a non-zero concentration of criteria pollutants (e.g., NO_x, CO, HC).

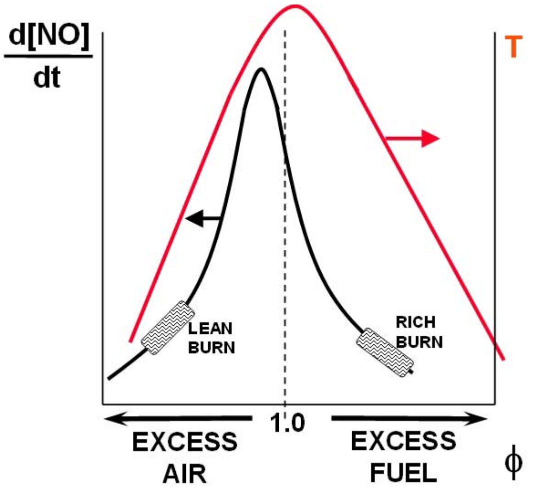


Fig. 2. Nitric Oxide Formation

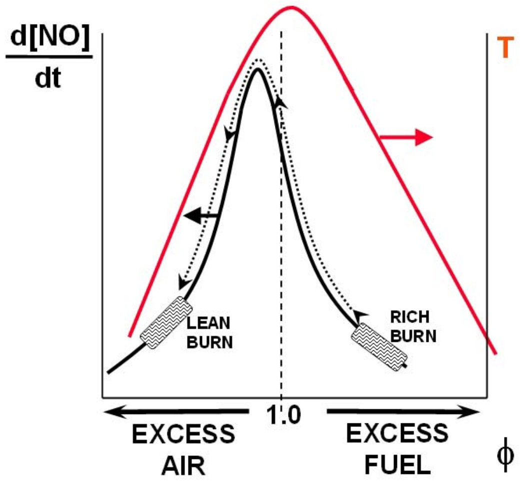


Figure 3 RQL Strategy

A major challenge for the RQL is the selection of combustor liner material. In the primary zone, for example, the use of air for cooling the liner wall is precluded in order to avoid the generation of near-stoichiometric mixture ratios and the associated production of nitrogen oxides in the vicinity of the wall. As a result, the temperature and composition of gases in the primary zone create a demanding, reducing environment for the liner material. The concentrations of hydrogen alone and the concomitant demands of hydrogen embrittlement in particular have combined to require a major investment in materials research in support of RQL technology.

A more demanding challenge is the design of the Quick-Mix section. A key to the success of the RQL is the efficacy of mixing the air with the effluent exiting the primary zone. The mixing of the injected air takes the reaction through the conditions most vulnerable for the high production of oxides of nitrogen (near stoichiometric conditions where both the temperature and oxygen atom concentrations are elevated). The challenge then is to rapidly mix air into the rich-burn effluent in order to rapidly create the lean-burn conditions (Figure 3). As a result, the label "Quick-Mix" is adopted to emphasize the requirement to rapidly mix the air and primary zone effluent. As a result, RQL research has historically focused on Quick-Mix section designs to establish the most rapid mixing.

3.2.1.3-2 Quick-Mix Zone

Numerous jet in crossflow studies have been conducted under non-reacting conditions to yield insight on such flow field characteristics as jet structure and penetration, jet entrainment of crossflow fluid, and the flow field distributions resulting from jet mixing.[2] Heated jets or a heated mainflow, or the doping of either the jets or mainflow with a tracer have allowed the measurement of scalars in the flow downstream of the jet orifices in order to quantify the convective and diffusive mixing efficacy. Early studies of jets in crossflow were motivated by the aerodynamics associated with (1) vertical/short takeoff and landing (V/STOL) aircraft and (2) primary and dilution jets on conventional gas turbine combustors with a focus on jet trajectory, centerline decay, and jet shape for unconfined single jets.[3] The interest in the Quick-Mix zone of the RQL combustor has constituted the focus of jet in crossflow studies over the past two decades.

A single round jet in a crossflow is presented in Figure 4. The jet enters the crossflow and is deflected downstream in response to the momentum of the cross flow. A recirculation zone can form in the near-wall downstream wake of the jet. The radial extent of jet penetration is governed by the angle of the jet relative to the crossflow, and the entry momentum of the jet in contrast to the momentum of the crossflow. A variety of non-reacting experiments have been used to establish empirical correlations for the maximum penetration of a single jet. For example:[4]

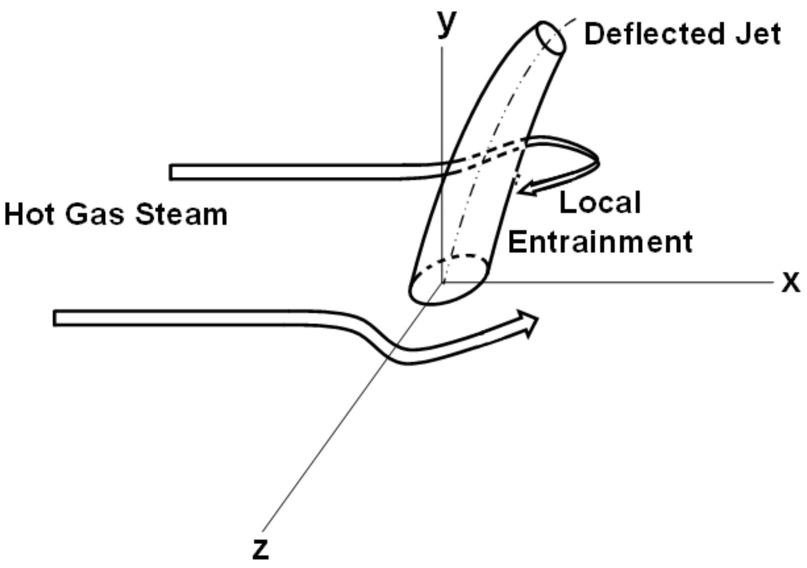


Fig. 4. Single Jet in Crossflow

$$Y_{max} = 1.15\left(d_j\right)\left(J^{0.5}\right)\sin\theta \tag{1}$$

Where:

Y_{max} = Maximum Radial Penetration of the Jet Centerline
dj = Diameter of the Jet Entry Orifice
J = Jet-to-Crossflow Momentum Flux Ratio = $\dfrac{\rho_{jets}\cdot V_{jets}^{2}}{\rho_{main}\cdot V_{main}^{2}}$ (2)
ρ = Density
V = Velocity
θ = Entry Angle of the Jet

In the gas turbine combustor, the jets are confined and the interaction between multiple jets is a major factor in dictating mixing behavior. As a result, studies has been conducted to address the mixing behavior associated with the mixing of primary and dilution jets in conventional gas turbine combustors; and optimizing the mixing section in the RQL combustor.[5] For multiple jets in a tubular duct, the correlation for the maximum penetration of a single jet must account for the effects of blockage:[6]

$$Y_{max} = 1.25\left(d_j\right)\left(J^{0.5}\right)MR \tag{3}$$

Where:

MR = Jet-to-Crossflow Mass Flow Ratio

MR is much higher for an RQL combustor (~ 2.5) in contrast to the conventional combustor (~ 0.25). Since the density and momentum-flux ratios J are about the same in the two configurations, the biggest difference between the jets in conventional and RQL combustors is orifice size.

Non-reacting studies have also been undertaken to evaluate geometrical features (e.g., orifice shape, number of orifices, axial staggering of orifices) and operating features (e.g., momentum flux ratio, density flux ratio, mass flow rate ratio) with the goal to optimize the mixing. Traditionally, such studies have defined "optimal mixing" as the shortest axial distance from the upstream edge of the jet orifice where a uniform radial profile is established of key mixing parameters (e.g., temperature, species concentration). The hypothesis is that the optimal mixing defined in this manner will minimize the production of nitrogen oxides. Due to the complex set of variables, many of the studies have benefited by a design of experiments statistical approach to explore the multiple factors that can affect jet mixing.[7] In addition to non-reacting experiments and use of design of experiments methods, modeling has been effectively employed both independent of and in conjunction with the experiments.[8]

While a variety of jet orifice configurations has been studied (e.g., triangular, slanted, tear-drop), no option has been identified that penetrates significantly farther or faster than a single, round jet. For a cylindrical configuration, a NASA design method developed by Holdeman and co-workers defined a correlation that is used to design the jet mixing section of an RQL combustor utilizing round hole jets.[9] The correlation, derived a study of jet-to-mainstream momentum-flux ratio, establishes the number of circular holes for optimum mixing:

$$n = \frac{\pi\sqrt{2J}}{C} \tag{4}$$

Where:

n = Number of Circular Jet Orifices to Optimize Mixing
J = Momentum Flux Ratio
C = Empirical Constant = 2.5

Reacting flow studies have also been conducted to complement the non-reacting studies and assess the impact of heat release on the mixing processes. Typically, a mixture of propane and air is used to generate a representative rich-burn effluent. A specially designed section is used to create a uniform presentation (e.g., temperature, velocity, composition, concentration) of the rich effluent to the mixing section. The injection of the quick-mix jet air results in the ignition of a reaction between the rich-burn effluent and the jet air (Figure 5). Measurements of temperature, species composition, and species concentration can then be made downstream of the jet orifices in order to establish the efficacy of mixing as a function of downstream distance.[10] The results from the reacting experiments reveal that the non-reacting experiments provide a satisfactory description of the mixing of jets in a crossflow. Overall, the jets need to penetrate to the half radius in order to maximize the mixing and avoid either under-penetration or over-penetration.[11]

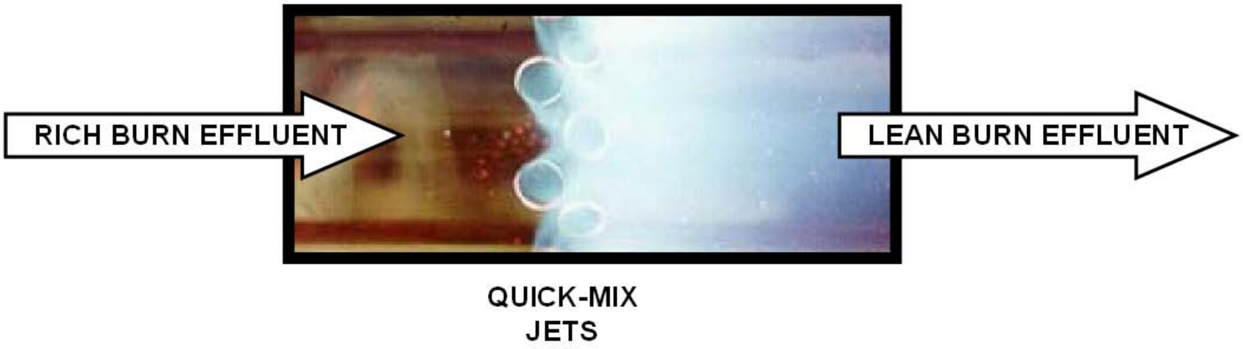


Fig. 5. Laboratory Model Combustor

Jet mixing in a crossflow has been studied in two primary mainstream geometries. The cylindrical geometry has been the most extensively researched and is directly relevant to combustor can configurations. In contrast, the modern annular combustor configurations have spawned investigations of jets in the crossflow of rectangular geometries. For each, Holdeman has established the following procedures to design the most rapid mixing, Quick-Mix section:[12]

Cylindrical Geometry

1. Typical Mass Ratio: 2.5
2. Typical Momentum Flux Ratio: 60
3. Optimal Number of Orifices:

$$n = \frac{\pi\sqrt{2J}}{C} \tag{5}$$

4. Orifice Size: Determined by the desired mass-flow ratio and the optimum number of orifices for the given momentum-flux ratio.

Rectangular Geometry

1. Typical Mass Ratio: 2.5
2. Typical Momentum Flux Ratio: 60
3. Optimal Orifice Spacing:

$$S/H = C/\sqrt{J} \tag{6}$$

Where:

S = Orifice Spacing
H = Channel Height

4. Orifice Size. For a given momentum-flux ratio, determined by the desired mass-flow ratio and the optimum orifice spacing. For a rectangular duct the number of orifices is infinite. For an annulus, the number of orifices will depend on the diameter and height of the mixing section.
5. Orifice Configuration. Can be either in-line or staggered. The selection will depend on the application, and include such factors as momentum-flux ratio. In-line configurations are usually preferred as the orifices are smaller. The optimum spacing for staggered jets is four times the optimum spacing for in-line configurations. As a result, the orifice diameter for staggered jets must be doubled for the same total orifice area.

3.2.1.3-3 Formation of Nitrogen Oxides

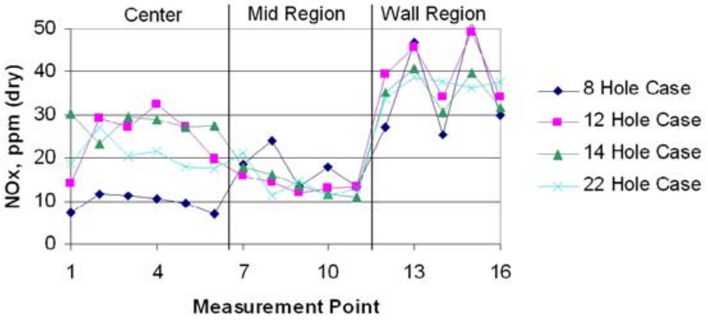
The hypothesis that the optimization of mixing in the Quick-Mix section will minimize the production of nitrogen oxides begs the question of proof. The first exploration of this relationship utilized the results of non-reacting experiments, and superimposed analytically the kinetics of NO_x production. The results suggested that the best mixer may not necessarily minimize NO_x emissions.[13]

In more recent research (Figure 6), oxides of nitrogen have been measured with the finding that the module designed to optimize mixing (12 holes) produces 15% more NO_x than an 8-hole module (Figure 6b).[14] These results also suggest that an aerodynamically "optimum" mixer may not minimize NO_x. It is noteworthy that the data for all modules show that high concentrations of NO_x occur in the wakes of the jets adjacent to the wall. This suggests that a significant production of NO_x likely occurs in the wakes of the jets, downstream of the orifices.

The research study reported in Figure 6 explored as well the effect of air preheat on NO_x formation. The main air and jet air streams were independently heated in order to assess the relative influence of independently preheating each flow. Three preheat conditions are presented in Figure 7. The first set of conditions is for no air preheat. This serves as an anchor to which the results for the elevated inlet air temperature conditions can be compared. The second set of conditions is for jet air preheat only (no main air preheat). The third set of conditions is for both jet air and main air preheat, representing the case usually encountered in practical combustors.

The results reveal the small impact of preheated jet air on NO_x. The jet air comprises over 70 percent of the total air flow, but preheating only the jet air results in relatively small increases in NO_x emissions compared to the case where both the main and jet air are preheated. The latter condition resulted in the largest NO_x production for all the modules. The small effect of preheating the jet air is counter intuitive to the expectation that preheating jet air should promote NO_x production via the thermal (Zeldovich) mechanism. The dominating influence of the main air preheat may be attributed to the total fixed nitrogen (TFN) production in the fuel-rich zone. In particular, the TFN generation in the fuel-rich zone, and its subsequent transformation to NO_x in the mixing zone, may be influential in governing the total NO_x emissions than expected.

a) Radial Profiles



b) Area-Weighted Average NO_x Concentrations

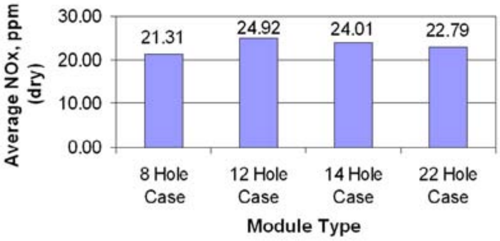
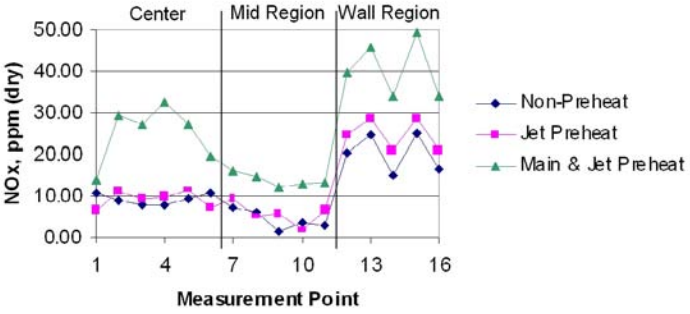


Fig. 6. Composite NOx Emissions Data

Source: *See note 17.*

a) Radial Profiles



b) Area-Weighted Average NO_x Concentrations

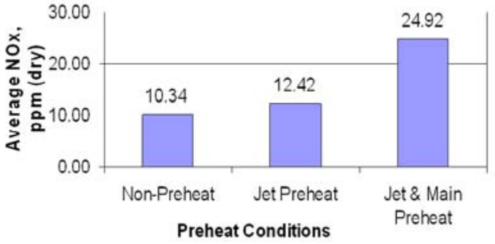


Fig. 7. Effect of Air Preheat on NO_x Concentrations

Source: *See note 17.*

The distributions of equivalence ratios reveal that preheat has a negligible effect on jet penetration. The equivalence ratio distributions are quite uniform which is also expected as the 12 hole configuration as an optimum mixer. In addition, the O_2 distributions serve as an indice for jet penetration and are virtually the same for all preheat conditions.

3.2.1.3-4 Conclusions

The Rich-Burn, Quick-Mix, Lean-Burn (RQL) combustor has evolved over the past three decades as a major strategy for the reduction of oxides of nitrogen from gas turbine engines. The concept has the attribute of high combustor stability due to the rich primary zone. While the RQL is deployed commercially in aeroengine applications, lean premixed options have been selected for stationary applications in lieu of the RQL in order to achieve lower NO_x emission. Niche applications in the stationary market, however, are driving a role for the RQL where fuels with complex compositions or fuels of varying composition are being encountered. This has prompted new research in the exploration of NO_x formation in RQL configurations. The hypothesis that optimal mixing in the Quick-Mix section will lead to the minimization of NO_x emission has been challenged by recent observations. In particular, the generation of nitrogen containing species in the Rich-Burn zone and subsequent processing in the Quick-Mix section may affect the emission of NO_x. While the RQL concept is inherently a low-NO_x generator, a further understanding of the primary zone chemistry and the coupling between the chemical kinetics and fluid mechanics in the Quick-Mix section may be required in order to optimize the RQL design. Fuels of varying composition and varying concentrations of fuel-bound nitrogen in stationary applications create a particular demand for this insight whereas the consistency of fuel composition in aeroengine applications allows insight derived from empirical evidence to be sufficient for the design of commercial RQL systems.

3.2.1.3-5 Notes

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1. Mosier, S.A., and Pierce, R.M., 1980. "Advanced Combustor Systems for Stationary Gas Turbine Engines, Phase I. Review and Preliminary Evaluation," Volume I, Contract 68-02-2136, FR-11405, Final Report, U.S. Environmental Protection Agency.
2. Holdeman, J.D., 1993. "Mixing of Multiple Jets with a Confined Subsonic Crossflow," Progress in Energy and Combustion Science, Vol. 19, pp. 31-70, August; Holdeman, J.D., Liscinsky, D.S., Oechsle, V.L., Samuelsen, G.S., and Smith, C.E., 1997. "Mixing of Multiple Jets With a Confined Subsonic Crossflow: Part I—Cylindrical Ducts," Journal of Engineering for Gas Turbines and Power, Vol. 119, No. 4, October, pp. 852–862; Holdeman, J.D., Liscinsky, D.S., and Bain, D.B., 1999. "Mixing of Multiple Jets With a Confined Subsonic Crossflow: Part II—Opposed Rows of Orifices in a Rectangular Duct," Journal of Engineering for Gas Turbines and Power, Vol. 121, No. 3, July, pp 551-562.
3. Margason, R.J., 1993. "Fifty Years of Jet in Cross Flow Research," Presented at Computational and Experimental Assessment of Jets in Cross Flow, AGARD Conference Proceedings 534, April; Demuren. A.O: Modeling Jets in Cross Flow. NASA Contractor Report 194965. August 1994;
4. Lefebvre, A.H., 1999. Gas Turbine Combustion, Taylor and Francis.
5. See Note 2.
6. See Note 4.
7. Hatch, M.S., Sowa, W.A., Samuelsen, G.S., and Holdeman, J.D., 1995,"Jet Mixing into a Heated Cross Flow in a Cylindrical Duct: Influence of Geometry and Flow Variations," Journal of Propulsion and Power, Vol. 11, No. 3, May-June, pp. 393–400; Kroll, J.T., Sowa, W.A., Samuelsen, G.S., and Holdeman, J.D., 2000. "Optimization of Orifice Geometry for Cross Flow Mixing in a Cylindrical Duct," Journal of Propulsion and Power, Vol . 16, No. 6, November-December, pp 929-936.
8. See Note 2.
9. See Note 2.
10. Leong, M.Y., Samuelsen, G.S., and Holdeman, J.D., 1999. "Mixing of Jet Air With a Fuel-Rich, Reacting Crossflow," Journal of Propulsion and Power, Vol. 15, No. 5, September-October, pp. 617-622; Leong, M.Y., Samuelsen, G.S., and Holdeman, J.D., 2000. "Optimization of Jet Mixing into a Rich, Reacting Crossflow," Journal of Propulsion and Power, Vol. 16, No. 5, September-October, pp. 729-735; Demayo, T.N, Leong, M.Y, Samuelsen, G.S., and Holdeman, J.D., 2003. "Assessing Jet-Induced Spatial Mixing in a Rich, Reacting Crossflow," Journal of Propulsion and Power, Vol. 19, No. 1, January-February, pp. 14-21.
11. See Notes 7 and 10.
12. See Note 2.
13. See Note 7.
14. Samuelsen, G.S., Brouwer, J., Holdeman, J.D., Vardarkas, M.A, and Leong, M.Y., 2006, "The Effect of Air Preheat and Number of Orifices on Flow and Emissions in an RQL Mixing Section," submitted for publication (see also NASA TM-1999-209431, 1999).

BIOGRAPHY

3.2.1.1 Conventional Type Combustion
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