A Report on:

# **Cross-flow Dilution Air Jet Studies**

Covering the period:

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# **Pratt and Whitney**

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Georgia Institute of Technology Atlanta, GA 30332 Phone: (404) 894-0013, FAX: (404) 894-2760 The goal of this project is to investigate the flame and flowfield characteristics of air jets injected into a cross-flow of high temperature combustion products, simulating an RQL type combustor. For the current reporting period (covering just over 4 months), the focus of the effort was to determine: 1) the operating range (especially the rich limit) for the existing main (low-swirl) burner facility and 2) the appropriate conditions for the cross-flow testing.

The main burner that will be used for the cross-flow studies is part of an existing facility (Figure 1). It is a low-swirl burner using natural gas and preheated air. Air from external tanks is mixed with natural gas fuel at the head of a 1.8 m (6 ft) long, 85 mm (3.36 in) dia. straight pipe section. The straight pipe section allows for the flow to be fully developed, and for the relatively cold fuel and preheated air to be fully premixed before the reactants enter the combustor. The air system is capable of supplying 907 g/s (2 lb/s) of air at up to 49 atm (720 psi) at a preheated temperature of up to 700 K. The natural gas system is capable of a maximum flow rate of 45.3 g/s (0.1 lb/s) at a maximum pressure of 51 atm (750 psi).

The mass flow rate of preheated air is metered across a 38 mm (1.5 in) orifice plate. The orifice plate is instrumented with an Omega PX725A-1KGI pressure transducer to measure the upstream air flow pressure, an Omega PX771A-025DI differential pressure transducer to measure the differential pressure and a K-type thermocouple to measure the air flow temperature.

The fuel flow rate is measured by a similarly instrumented 38 mm (1.5 in) orifice plate. The fuel temperature is not measured as it is assumed to be close to the nominal room temperature of 300 K. The fuel line pressure is measured using an Omega PX181B-500G5V pressure transducer. An Omega PX771A-100WCDI differential pressure transducer measures the pressure difference across the orifice plate.



Figure 1. Picture of existing combustion facility.



Figure 2. Schematic of LSB main burner.

A detailed view of the LSB in the pressure chamber is shown in Figure 2. At the inlet of the combustor, the diameter of the pipe converges from 85 mm (3.36 in) to the outer diameter of the

swirler, 38 mm (1.5 in) through a nozzle. The swirler consists of an outer annular swirled section with 16 vanes surrounding a central unswirled section covered by a perforated plate. The targeted mass flow split is 0.5, i.e., two-thirds of the air passes through the vanes, while one-third passes through the central section. The swirler is located 38 mm (1.5 in) upstream of the dump plane at the entrance of the combustor. The main combustor is 300 mm (12 in) long, and 115 mm (4.5 in) in diameter. The expansion ratio of the flow from the inlet to the combustor is 3:1.

Based on initial discussions with Pratt, it was determined that a targeted value to simulate the appropriate main combustion products would require the main combustor air inlet temperature to be ~600K. This condition was tested to determine the operability range of the LSB in terms of equivalence ratio. Table 1 shows the range available with the minimum equivalence ratio being about 0.6; though it is expected that the minimum equivalence ratio of interest will be 0.8. The maximum value, 1.3, is based on the point where main burner instabilities occur. This series of stability mapping yielded the basis for initial designs of the actual test facility.

Table 1: Equivalence Ratio							
Range for Main Burner							
T_preheat	600	К					
φmin	<0.8						
φmax	1.3						

The requirements for the rig simulations (at atmospheric pressure conditions) were the second major effort in the first period of this program. A number of design variables were identified as likely candidates for controlling mixing and combustion of the air dilution jets with the main flow combustion products, based on an extensive review of the jet in cross flow literature (Appendix A). These include: momentum ratio of jets to main flow, air preheat temperature, main flow equivalence ratio, overall equivalence ratio, main flow velocity, and ratio of jet diameter to jet spacing. Value ranges for some of these parameters were chosen in cooperation with Pratt & Whitney (PW) personnel to provide a reasonable match to PW combustor conditions.

After determining that the possible equivalence ratio range was between 0.8 and 1.3, the initial parameter/design was set based upon the predetermined ranges from PW. A series of calculations was performed to examine the range of achievable conditions the flow facility. Based upon these calculations, the RQL test section was chosen to be 3 inches (76.2 mm) high and 4 inches (101.6 mm) wide. This test section will allow for 5 air jets, 2 on the top and 3 on the bottom, interlaced such that each of the three central jets is between two others from the opposite wall. To keep the scale of the jets comparable to the PW system, the inner diameter of each jet was chosen to be 0.546". This allows the jets to be fabricated from  $\frac{1}{2}$ " schedule 80 pipe. Each air injector will be supplied with 1.5 to 2 times the main flow air flow rate.

Tables 2 and 3 show parameters for two different equivalence ratios and two different air split ratios.

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# Appendix

# Literature Review: Jets in Crossflow with Emphasis on Results Relevant to RQL Combustion Systems

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# Contents

1	Introduction	2
2	Single Non-Reacting Jets in Crossflow         2.1       Momentum Methods, Vortex Methods, Similarity Methods and Trajectory Scaling         2.2       Flow Visualization and Optical Diagnostics         2.3       Dynamics and Stability of a Jet in Crossflow         2.4       Numerical Methods and Simulations	<b>2</b> 2 5 6 11
3	Single Reacting Jets in Crossflow3.1Flow Visualization and Optical Diagnostics3.2Numerical Methods and Simulations	<b>12</b> 12 14
4	Multiple Non-Reacting Jets in Crossflow         4.1 Experimental Characterization         4.2 Numerical Methods and Simulations	<b>15</b> 15 18
5	Multiple Reacting Jets in Crossflow5.1 Empirical Results, Mixing Studies and Pattern Factor Optimization5.2 Numerical Methods and Simulations	<b>19</b> 19 20
Bi	ibliography	<b>22</b>

### 1 Introduction

The purpose of this document is to compile and organize previous jet in crossflow literature as the foundation for a detailed study of the quench (or dilution) jets of a Rich-Quench-Lean combustor. An extensive body of literature exists for jets in crossflow. The breadth and depth of this literature can be attributed to both the practical importance of the flow field in engineering technologies and the rich fluid dynamic structure of the flow field. The jet in crossflow provides a relatively simple and efficient means to rapidly mix two reactant streams. The flow field is highly three-dimensional and almost always quite turbulent. The non-reacting jet in crossflow has been studied at least since the middle of the 20<sup>th</sup> century. The reacting jet is less robust than that of the non-reacting jets due to experimental and theoretical complications caused by chemical reactions.

### 2 Single Non-Reacting Jets in Crossflow

### 2.1 Momentum Methods, Vortex Methods, Similarity Methods and Trajectory Scaling

#### 2.1.1 The round turbulent jet in a cross-wind

[Keffer and Baines, 1962]

#### 2.1.2 Experiments on a Turbulent Jet in a Cross Flow

[Kamotani and Greber, 1972]

#### 2.1.3 Physical characteristics of subsonic jets in a cross-stream

[Chassaing et al., 1974]

#### 2.1.4 The near field in the mixing of a round jet with a cross-stream

[Moussa et al., 1977]

#### 2.1.5 Experimental investigation of jets in crossflow

[Andreopoulos and Rodi, 1984]

#### 2.1.6 Structure and mixing of a transverse jet in incompressible flow

[Broadwell and Breidenthal, 1984]

#### 2.1.7 On the structure of jets in a crossflow

[Andreopoulos, 1985]

#### 2.1.8 A jet in crossflow

[Needham et al., 1988]

#### 2.1.9 The dynamics of the near field of strong jets in crossflows

[Coelho and Hunt, 1989]

#### 2.1.10 Effects of Swirl and High Turbulence on a Jet in a Crossflow

[Kavsaoglu and Schetz, 1989]

#### 2.1.11 Separated Flow Upstream of a Jet in a Crossflow

[Krothapalli et al., 1989]

#### 2.1.12 Dynamics of vortex rings in crossflow

[Chang and Vakili, 1995]

#### 2.1.13 Jets Deflected in a Crossflow

[Morton and Ibbetson, 1996]

#### 2.1.14 Transverse jets and jet flames. Part 1. Scaling laws for strong transverse jets

[Hasselbrink Jr. and Mungal, 2001a]

The first part of a two-part sequence aimed to develop usable similarity theory for transverse jets and accompanying scaling laws for concentration and velocity profiles. There is extensive PIV and PLIF data in the second study, but the goal of the first is strictly to develop similarity theory. The authors rely heavily on the previous work by Broadwell and Breidenthal [Broadwell and Breidenthal, 1984] and the asymptotic methods of Barenblatt & Zeldovich [Barenblatt and Zel'dovich, 1972] and Barenblatt [Barenblatt, 1996]. Their general approach divides the flow field into a jet-like region surrounding the injection site and a wake-like region in the far-field. The resulting derivation is very similar to some previous work but differs significantly in the characterization of the CRVP. Notably, the authors focus on relatively high Reynold's number jets, which are clearly turbulent, and study moderate to very-high blowing ratios ( $r = (\rho_j u_j^2/\rho_{\infty} u_{\infty}^2)^{1/2}$ ). An effort is made to link high-momentum-flux-ratio jets-in-crossflow with free jets existing into a quiescent environment. A subsonic wind tunnel is used to collect data, although very little data is presented in Part 1. Acetone PLIF is utilized in the non-reacting experiments.

- Several restrictive assumptions are made to make the problem tractable including the following:
  - 1. For instance, the velocity field is assumed to be approximately parallel to the centerline inside the control volume.
  - 2.  $u \to 0$  and  $v \to v_{\infty}$  where u is parallel to the jet and the crossflow, v, is in the y-direction.
  - 3. In the near-field, the velocity is dominated by the u-component. In the far-field, the velocity is dominated by the v-component.
- Suggests a definition of coherent structures–"dominant vortical structures which represent the hope of a mechanistic rather than [only] statistical understanding of turbulence"
- Vortex rings rotate *towards* the crossflow as they are swept away by it.
- Trajectory can be defined as  $\frac{dx}{dy} = \frac{u_c}{v_c}$ . With appropriate expressions for velocity this can be integrated to find the trajectory.

- The near-field region of a JICF can be compared to a free jet. In the free jet (or without cross-flow), the concentration profiles normalized by  $\frac{x}{d}$  and plotted verus  $\frac{y}{x}$  should collapse into a single Gaussian-like curve. This situation is nearly realized for very high blowing ratios.
- Note: Acetone PLIF signal must be corrected for laser sheet intensity distribution, background signal and the absorption of laser energy by acetone.
- Another measure to compare against the free jet is the centerline concentration decay. Withour a crossflow, this is predicated by similarity analysis to decay as  $\xi = \frac{5.0}{\left(\frac{x}{d}\right)}$ . We would only expect this scaling to hold for high momentum flux ratios for jets in crossflow. It should be noted that similarity analysis of this type has a lower bound on its region of validity as well  $\left(\frac{x}{d} > 10\right)$ .
- The similarity scaling for a wake can be used in the farfield with somewhat decent results. The data presented suggest that blowing ratio greater than 20 is required for a wake-type similarity scaling to hold.
- Based on similarity analysis, authors find the surprising result that "the idealized vortex pair has a constant angle of inclination throughout the jet:  $\alpha_{cvp} = \arctan(v_{\infty}/u_j)$ ."
- The following reasons all contribute to scatter in transverse jet trajectory data:
  - 1. Variation in the centerline definition including all of the following:
    - (a) Maximum velocity criteria
    - (b) Maximum scalar concentration criteria
    - (c) Center streamline criteria
  - 2. Variation in experimental conditions
  - 3. Various choices of correlating functions as a result of differing simplifying assumptions used in derivations
  - 4. Variation in the determination of  $u_j$ , which has a non-negligible distribution that is often unknown
  - 5. Variation in the range of blowing ratio and/or Reynold's number explored
  - 6. Variation in the calculation of blowing ratio due to variation in the jet exit velocity profile
- In both the near and far-field,  $\delta \sim x$  where  $\delta$  is the local characteristic width of the jet. The proportionality constant, however, may vary between the near and far-field. This scaling leads to trajectory in the far-field of the form

$$\left(\frac{x}{rd}\right) \sim \left(\frac{y}{rd}\right)^{1/3}$$

which is the classical scaling for an axisymmetric wake.

- Several restrictive assumptions were made in this work including the following:
  - 1. Pressure terms are negligible in the momentum conservation relations (equivalently that  $r^2 \gg 1$ ).
  - 2. Image vortices might be expected, especially at low blowing ratios, but are not included in the analysis.
  - 3. The 'virtual origin' of the jet is not considered.
  - 4. The interaction between the boundary layer and the jet is not included.
  - 5. Detailed velocity profiles of the jet exit are not measured.
- The centerline path can be determined by integration.

$$s = \int_0^s ds = \int_0^s \left[ \left( \frac{dx^2}{dy^2} \right) + 1 \right]^{1/2} dy$$

#### 2.1.15 A jet at an oblique angle to a cross-flow

[Kikkert et al., 2009]

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#### 2.1.16 Inclined Jet in Crossflow Interacting with a Vortex Generator

[Zaman et al., 2010]

#### 2.2 Flow Visualization and Optical Diagnostics

#### 2.2.1 Vortical structure in the wake of a transverse jet

[Fric and Roshko, 1994]

#### 2.2.2 Horseshoe vortex systems resulting from the interaction between a laminar boundary layer and a transverse jet

[Kelso and Smits, 1995]

#### 2.2.3 Crossflow Mixing of Noncircular Jets

[Liscinsky et al., 1996]

#### 2.2.4 An experimental study of round jets in cross-flow

[Kelso et al., 1996]

#### 2.2.5 Kidney and anti-kidney vortices in crossflow jets

[Haven and Kurosaka, 1997]

#### 2.2.6 Manipulation of a jet in cross flow

[Gogineni et al., 1998]

#### 2.2.7 Mixing, structure and scaling of the jet in crossflow

[Smith and Mungal, 1998]

#### 2.2.8 Penetration and Mixing of Fully Modulated Turbulent Jets in Crossflow

[Johari et al., 1999]

**2.2.9** On the development of large-scale structures of a jet normal to a cross flow [Lim et al., 2001]

#### 2.2.10 Experimental study of a jet in a crossflow at very low Reynolds number

[Camussi et al., 2002]

#### 2.2.11 Short-hole jet-in-crossflow velocity field and its relationship to film-cooling performance

[Peterson and Plesniak, 2002]

#### 2.2.12 Evolution of jets emanating from short holes into crossflow

[Peterson and Plesniak, 2004a]

2.2.13 Simultaneous measurements of scalar and velocity field evolution in turbulent crossflowing jets

[Su and Mungal, 2004]

#### 2.2.14 Scalar mixing in a confined rectangular jet in crossflow

[Plesniak and Cusano, 2005]

#### 2.2.15 Effects of jet velocity profiles on a round jet in cross-flow

[New et al., 2006]

#### 2.2.16 Reynolds-number effects and anisotropy in transverse-jet mixing

[Shan and Dimotakis, 2006]

#### 2.2.17 A turbulent jet in crossflow analysed with proper orthogonal decomposition

[Meyer et al., 2007]

# 2.2.18 Flow structure and skin friction in the vicinity of a streamwise-angled injection hole fed by a short pipe

[Peterson and Plesniak, 2007]

#### 2.3 Dynamics and Stability of a Jet in Crossflow

#### 2.3.1 Vortex shedding from a turbulent jet in a cross-wind

[McMahon et al., 1971]

#### 2.3.2 On the inviscid instability of a circular jet with external flow

[Michalke and Hermann, 1982]

#### 2.3.3 An Analytical Model for the Vorticity Associated with a Transverse Jet

[Karagozian, 1986a]

#### 2.3.4 Lock-in of vortices in the wake of an elevated round turbulent jet in a crossflow

[Eiff et al., 1995]

# 2.3.5 Influence of a counter rotating vortex pair on the stability of a jet in cross flow: an experimental study by flow visualizations

#### [Blanchard et al., 1999]

An experimental study is performed to investigate the instability of a jet in crossflow. The jet is a fairly high aspect ratio slot with the long edge transverse to the flow direction. The work focuses on instability of the counter rotating vortex pair. Two techniques are utilized for flow visualization: particle tracking velocimetry (PTV) and laser-induced fluorescence tomography (LIFT). The authors utilize experimental results to question whether the traditional "Kelvin-Helmholtz" instability mechanism is the correct explanation for the commonly observed transverse vortical "shear layer rollup" seen on the leading edge of a jet injected into a crossflow. An attempt is made to explain the transverse vortical structures through a global hydrodynamic phenomena intimately linked to the counter rotating vortex pair. The theory of Landman and Saffman [Landman and Saffman, 1987] provides additional support for this hypothesis. Note that confinement, as mentioned by the authors, was not explored in this study and may be important.

Water is used for both the crossflow and the jet. The  $Re_{cf}$  is low ( $\leq 1000$ ), usually ranging from 300 to 500, and the velocity ratio is varied from 1.5 to 6.5. The water supply for the jet is mixed with a fluoresceine salt for the LIFT diagnostics. The PTV diagnostic, however, seeds only the mainstream flow with larger ( $60 \rightarrow 80 \mu m$ )polyamid particles. In the LIFT data, Schmidt number is maintained above  $10^3$  to avoid the influence of molecular diffusion on the flow diagnostics. The PTV measurements, conversely, require particles with density approximately equal to the working fluid and particles exhibiting isotropic scattering.

Notable observations include the following:

- The diagram of jet stability shows unconditional stability for  $Re_{cf} \leq 300$  regardless of velocity ratio or momentum ratio.
- The individual vortices of the CRVP appear to grow linearly in size until X/e (axial length nondimensionalized by slot size) of about 25. This would be interesting to study in the reacting case because CRVP growth directly affects pattern factor.
- The appearance of transverse vortical structures (instabilities) is a function of both  $Re_{cf}$  and velocity ratio  $\alpha = U_j/U_{cf}$ . There are regions of the space mapped by these parameters that do not exhibit instability. Does this phenomena exist in the reaction case? How is the region of stability affected?
- For all cases studied, the vortex structures are observed to start at approximately  $X/e \sim 10.0$ .
- The K-H hypothesis requires some very specific behavior that is not necessarily observed in this study. Namely, the K-H instability is an amplification of small local disturbances based on the interaction at the shear region between the jet and the crossflow. The K-H mechanism should have a Gaussian histogram, but the author's data reveals a dominant frequency isolated among small peaks. The K-H mechanism does not predict the unconditionally stable regime at  $\alpha < 3$  for relatively high Reynold's numbers.
- To first order, one vortice of the CRVP can be described as a "vortex with a constant vorticity in a (y,z) plane and convected with constant  $\vec{u}$ ".

- The rotation rate of the CRVP is seen to have a peak along the axial direction, possibly corresponding with the end of the 3D recirculation region behind the jet.
- Saffman's[Landman and Saffman, 1987] stability theory is used to explain the observed dynamics. A minimum and maximum wavenumber is predicted. Cases are stable when the  $\lambda_{min} > \lambda_{max}$ . Analysis suggests that the amplification of an instability associated with the eccentricity of the CRVP may drive the eddy occurrence along the windward side of the jet. An estimate is given for the rate of spread. This technique may be of interest for the reacting case.

#### 2.3.6 Dynamics and Control of an Isolated Jet in Crossflow

[Narayanan et al., 2003]

#### 2.3.7 Control of Vorticity Generation in an Acoustically Excitepd Jet in Crossflow

[Karagozian et al., 2005]

#### 2.3.8 Linear Stability Analysis of Jets in Cross Flow

[de B. Alves et al., 2005]

#### 2.3.9 Control of Transverse Jet Shear Layer Instabilities

[Davitian et al., 2006]

#### 2.3.10 Optimization of Controlled Jets in Crossflow

[Shapiro et al., 2006]

#### 2.3.11 Scaling of Fully Pulsed Jets in Crossflow

[Johari, 2006]

#### 2.3.12 Transverse-jet shear-layer instabilities. Part 1. Experimental studies

[Megerian et al., 2007]

UCLA's group investigates the shear-layer instabilities associated with a jet in crossflow. Attention is devoted to both natural and forced instabilities for an air jet injected into a crossflow of air. The nature of these instabilities is quantified using hot-wire probes to record vertical velocity fluctuations along the mean path of the shear-layer on the windward side of the jet. The authors note that the character of instabilities changes significantly for high and low velocity ratios, with a critical point near  $U_j/U_{cf} = 3.5$ for the flush-injected jet. The lower velocity ratios exhibit strong fundamental modes near the jet exit that are insensitive to external forcing. This behavior is characteristic of globally unstable flows and is consistent with the work of previous authors who noted that only very strong forcing with square wave signals could noticeably alter low velocity ratio transverse jets. High velocity ratio jets, conversely, exhibit multiple closely spaced peaks which move closer to the jet exit as the velocity ratio is decreased. The dominant frequency in high velocity ratio cases is subject to mode-locking and switching phenomena.

Experiments were conducted in a low-speed wind tunnel at two different Reynolds numbers: Re = 2000and Re = 3000. Velocity ratios were in the following range:  $1 \leq U_j/U_{cf} \leq 10$ . Both a flush nozzle and an elevated nozzle were used for testing. Each nozzle had a nearly identical fifth-order polynomial shape and was designed for a nearly perfect top-hat profile. Upstream velocities ranged from 0m/s to 7.2m/s. The turbulence intensity of the crossflow was low ( $\leq 1.5\%$ ) Forcing was accomplished using a subwoofer in the jet supply plenum. Low level sinusoidal excitation was chosen to study the convective or global instability tendencies of the flow field.

- The momentum thickness of the jet exit is a nice parameter to use, particularly as a length scale for excitation in the shear layer. The chart on pg. 102 of the article shows a number of momentum thickness for the jet. It is noteworthy that the upstream momentum thickness is often as much as twice (and sometimes exactly twice) the downstream momentum thickness for the low velocity ratio cases that tend to exhibit global instability.
- Contour plots displaying Strouhal number, non-dimensional path length <sup>s</sup>/<sub>D</sub> and velocity oscillation amplitude were utilized to characterize the nature of flow instabilities in forced and unforced cases.
- A strong shift in shear-layer behavior is observed at  $U_j/U_{cf} = 3.5$ . The jet tends to exhibit global instability traits below this velocity ratio and convective instability at higher velocity ratios. This observation has important implications for how jets might be forced to encourage mixing or increase penetration depth.
- At low velocity ratios the jet shear-layer is relatively insensitive to low-level sinusoidal forcing, but exhibits strong dominant modes of instability characteristic of global instability. Harmonics are very clear in contour plots for amplitude of oscillation versus frequency.
- At high velocity ratios the jet shear-layer exhibits obvious response to low-level sinusoidal forcing and demonstrates behavior strongly indicative of convective instability. Namely, the excitation frequency is clearly excited while the naturally dominant mode is suppressed. The oscillation is periodic in time along the shear layer and suggests convective instability.

#### 2.3.13 Transverse-jet shear-layer instabilities. Part 2. Linear analysis for large jet-tocrossflow velocity ratio

[De B. Alves et al., 2008]

# 2.3.14 A uniformly valid asymptotic solution for a transverse jet and its linear stability analysis

[Kelly and de B Alves, 2008]

#### 2.3.15 Self-sustained global oscillations in a jet in crossflow

[Schlatter et al., 2009]

#### 2.3.16 Global stability of a jet in crossflow

[Bagheri et al., 2009]

#### 2.3.17 Analysis and reconstruction of a pulsed jet in crossflow by multi-plane snapshot POD

[Vernet et al., 2009]

Study utilizes stereoscopic particle image velocimetry (SPIV) to study unexcited and excited single jets in crossflow in a water tunnel. Analysis focuses on explaining the differences between pulsed and continuous jets in crossflow. Analysis methods include Q criterion and proper orthogonal decomposition (POD). Results are presented for instantaneous, phase-averaged and fluctuating velocity fields. Water jets are

injected into the water tunnel at velocity ratio R = 1 and  $Re_j = 500$ . Excitation frequency is f = 1Hz with amplitude of forcing  $A \leq (0 \rightarrow 2) \times V_{crossflow}$ .

Notable observations include the following:

- Authors utilize Johari classification scheme[Johari, 2006] for pulsed jets in crossflow based on duty cycle and stroke ratio. Stroke ratio is defined as the injection length for a given temporal pulse  $(Stroke = \frac{\tau \cdot V_j}{L_{flow}}).$
- Velocity fields with three components are presented for six planes (four x-z and two y-z). For the forced cases, data is recorded in phase with 200 instantaneous images at 20 points distributed along the excitation period.
- Q criterion is the second invariant of the velocity gradient tensor  $(Q = 0.5(||\Omega||^2 ||S||^2))$ . Note that the Q criterion is defined from the symmetric and antisymmetric portion of the strain rate tensor. A region with positive Q criterion represents a vortex ring, while a region of negative Q criterion represents a shear layer.
- Forcing in this work is at f = 1Hz, but the shear layer instability is approximately  $f_{KH} = 0.25Hz$ .
- Q criterion of the unforced jet reveals that vortex formation does not start at the jet exit but above the jet exit in the wake region. The forced jet exhibits vortex formation at both the windward and leeward side of the jet injection site.
- Forcing changes the structure of the jet in the wake region. The forced jet wake is characterized by alternating regions of shear and vortex rings that are attenuated relatively quickly. Note that the far-field of both the forced and unforced jet are very similar, confirming that excitation attenuation is very rapid.
- POD is a useful tool for uncovering energy distribution information and efficiently communication information about a flow field. The book by Holmes[Holmes et al., 1998] would be a good reference for this material. Recently, other researchers [Druault and Chaillou, 2007, Meyer et al., 2007] have used POD to analyze flow structures in turbulent flows and jets in crossflow, respectively.
- The first POD mode usually corresponds to the mean flow. In the unforced case, the 2<sup>nd</sup> and 3<sup>rd</sup> modes have nearly identical energy content. The combination of those two modes represents about 10% of the flow energy. The fourth mode represents only about 4% of the flow energy. Authors also present a phase diagram with circular patterns of temporal coefficients, indicating strong correlation between the second and third modes.
- Note: instantaneous POD is only performed on the unforced case because there is no phase to average.
- Note: POD of the phase-averaged pulsed jet does reveal the forcing but only if the interrogation plane is sufficiently close to jet exit. Planes removed from the region of excitation show no effects of the forcing in their POD analysis.
- Authors use four y-plane slices to reconstruct the 3-D flowfield. Technique shows promise but the study in question lacked sufficient temporal resolution to resolve the forced and natural modes. The natural modes have non-negligible energy content and should be included.

#### 2.3.18 Direct Numerical Simulation of pulsed jets-in-crossflow

[Muldoon and Acharya, 2010]

#### 2.3.19 Optimization of pulsed jets in crossflow

[Sau and Mahesh, 2010]

#### 2.3.20 Strategic Control of Transverse Jet Shear Layer Instabilities

[Davitian et al., 2010]

#### 2.3.21 Transverse jets and their control

[Karagozian, 2010]

#### 2.4 Numerical Methods and Simulations

#### 2.4.1 On the vorticity dynamics of a turbulent jet in a crossflow

[Sykes et al., 1986]

#### 2.4.2 Vortex ring pairs: numerical simulation and experiment

[Weidman and Riley, 1993]

#### 2.4.3 Large-eddy simulations of a round jet in crossflow

[Yuan et al., 1999]

#### 2.4.4 LES of Jets in Cross Flow and Its Application to a Gas Turbine Burner

[Schlüter and Schönfeld, 2000]

#### 2.4.5 Study of trajectories of jets in crossflow using direct numerical simulations

[Muppidi and Mahesh, 2005]

#### 2.4.6 Vorticity Structure and Evolution in a Transverse Jet with Algorithms for Scalable Particle Simulation

[Marzouk, 2004]

#### 2.4.7 Numerical Simulation and Experiments of Jets in Cross Flow

[Li et al., 2006]

#### 2.4.8 Vorticity structure and evolution in a transverse jet

[Marzouk and Ghoniem, 2007]

#### 2.4.9 A numerical investigation of a jet in oscillating crossflow

[Kremer et al., 2007]

# 2.4.10 Large-Eddy-Simulation Modeling for Aerothermal Predictions Behind a Jet in Crossflow

[Jouhaud et al., 2007]

#### 2.4.11 Mixing in Circular and Non-circular Jets in Crossflow

[Salewski et al., 2008]

#### 2.4.12 Large-Eddy Simulation of a Round Jet in Crossflow

[Ziefle and Kleiser, 2009]

#### 2.4.13 Computational Modeling of Turbulent Mixing of a Transverse Jet

[Ivanova et al., 2011]

#### 3 Single Reacting Jets in Crossflow

#### 3.1 Flow Visualization and Optical Diagnostics

3.1.1 An Experimental and Theoretical Study of the Turbulent Diffusion Flame in Cross-Flow

[Botros and Brzustowski, 1979]

#### 3.1.2 Effects of Heat Release and Flame Distortion in the Transverse Fuel Jet

[Karagozian and Nguyen, 1986]

#### 3.1.3 Effects of Heat Release and Flame Distortion in the Transverse Fuel Jet

[Karagozian, 1986b]

#### 3.1.4 Predictions of a Turbulent Reacting Jet in a Cross-Flow

[Fairweather et al., 1991]

#### 3.1.5 The Stability and Visualized Flame and Flow Structures of a Combusting Jet in Cross Flow

[Huang and Chang, 1994a]

#### 3.1.6 Coherent Structure in a Combusting Jet in Crossflow

[Huang and Chang, 1994b]

#### 3.1.7 Some observations of a large, burning jet in crossflow

[Mungal and Lozano, 1996]

#### 3.1.8 Thermal and Concentration Fields of Burner-Attached Jet Flames in Cross Flow

[Huang and Yang, 1996]

#### 3.1.9 Observations on the Stabilization Region of Lifted Non-Premixed Methane Transverse Jet Flames

[Hasselbrink Jr. and Mungal, 1998]

#### 3.1.10 Transverse jets and jet flames. Part 2. Velocity and OH field imaging

[Hasselbrink Jr. and Mungal, 2001b]

#### 3.1.11 Turbulent Jet Flames in a Crossflow: Effects of Some Jet, Crossflow, and Pilot-Flame Parameters on Emissions

#### [Bandaru and Turns, 2000]

Study considers fuel jets injected into cold crossflow of air. Four fuels of varying soot propensity (methane, propane, ethylene, syngas) are examined. Emissions data for each fuel at various momentum flux ratios and crossflow velocities are reported. CO, NO, NO<sub>2</sub> and UHC measurments are performed. Rudimentary radiation measurements are made and some attempt is made to correlate  $NO_x$  concentration and radiative losses, although only from a qualitative perspective. Useful tables detailing the history of fuel jet flames in crossflow are provided. Interesting trends are observed in the emissions data that suggest macroscopic combustion performance is both sensitive to chemistry and near-field flow variations. Possible quenching and alternative chemical pathways are suggested to explain some trends. In general the data supports a case for more advanced measurements and provides some likely explanations but is far from conclusive.

Interesting points from the article:

- A useful chart is provided to identify previous experimental work for fuel jets injected into air crossflows.
- Authors utilize the potential core of a free jet for the crossflow. Note that this work uses a pipe injection and not a flush injection plane.
- Authors define a flame Froude number  $Fr_f = \rho_j u_o^2 \pi d_o^2 / [4(\rho_o \rho_\infty)V_f g]$  and a crossflow Froude number  $Fr_{cf} = \rho_\infty u_\infty^2 \pi A_{f,frontal} / [(\rho_o \rho_\infty)V_f g]$  where  $V_f$  = volume of the visible flame =  $(\pi W_x W_z L_f / 12)$ .
- $NO_2/NO$  ratio and CO concentration are interesting parameters to consider. This ratio could be more sensitive to near-field flow changes, whereas NO may be more sensitive to global flow parameters because of the far-field influence.
- These authors consider a syngas fuel mixture and observe very different flame holding than normal hydrocarbon fuels.
- These authors observe significant emissions sensitivity when the fuel jet is methane, propane, ethylene or syngas. This suggests that the chemical composition approaching the jet in reacting crossflow may be important. Need to think about what physical change is driving this observation. Radiation is suggested by Turns and Bandaru, chemical pathways/flame speeds are also likely to be very important.

- Piloted jet in crossflow flames exhibit substantially less sensitivity to changes in momentum ratio or crossflow velocity. The effect on UHC is very strong.
- Fuels with different sooting propensity were intentionally selected. The high-sooting ethylene flame showed much more variation in  $NO_x$  with crossflow velocity changes, possibly because of its high radiative losses.
- The near-field is observed to be important as a flame anchoring region and a region where any escaped fuel can cause emissions problems downstream. In the hydrocarbon fuels, escaped fuel from lifted flames in crossflow in the near-field is prone to re-enter the reacting region and contribute to  $NO_x$  formation via the Fenimore-Prompt mechanism.

# 3.1.12 Simultaneous measurements of velocity and CH distribution. Part II: deflected jet flames

[Han and Mungal, 2003]

#### 3.1.13 Impacts of a jet's exit flow pattern on mixing and combustion performance

[Nathan et al., 2006]

#### 3.1.14 Flowfield Characteristics of a Confined Transverse Slot Jet

[Ahmed et al., 2008]

**3.1.15** Optimal discharge placement in plasma-assisted combustion of a methane jet in cross flow

[Kim et al., 2008]

#### 3.1.16 Fluidic Flame Stabilization in a Planar Combustor Using a Transverse Slot Jet

[Ahmed and Forliti, 2009]

#### 3.1.17 On the Flame and Vorticity Characteristics of a Fluidically Stabilized Premixed Turbulent Flame

[Ahmed and Forliti, 2010]

#### 3.2 Numerical Methods and Simulations

**3.2.1** Three-dimensional direct numerical simulation of a turbulent lifted hydrogen jet flame in heated coflow: flame stabilization and structure

[Yoo et al., 2009]

# **3.2.2** Direct numerial simulation of flame stabilization downstream of a transverse fuel jet in cross-flow

#### [Grout et al., 2010]

Direct numerical simulation is utilized to examine an  $N_2$  diluted  $H_2$  fuel jet injected normally from a square orifice into a crossflow of heated air. Study is aimed at fundamental understanding of flame stabilization mechanism in premixed  $H_2 - Air$  flames characteristic of modern low  $NO_x$  gas turbines. The danger of flashback is listed as a motivating factor.

The physical domain for simulation is  $25mm \times 20mm \times 20mm$  (x,y,z). Crossflow air is supplied at 750K and fuel mixture is injected at 423K. Flow parameters are as follows:  $Re_j = 3980$ ,  $U_j = 55m/s$ ,  $U_j/U_{cf} = 4.5$ ,  $\sqrt{\rho_j U_j^2/\rho_{cf} U_{cf}^2} = 3.4$ , and  $U'_{cf}/U_{cf} = 0.1$ . S3D finite difference code solves the compressible Navier-Stokes equations with a nine species, 19 reaction mechanism. The lower wall is solid and assumed inert. The turbulent upstream crossflow is initialized by separate DNS solution with non-recycled inlet condition.

Notable results include the following:

- Time averaged data is presented over a window reflecting a single flow-through time based on the mean inlet velocity.
- Data suggests that flame stabilizes (in the mean) 1.5-2 jet diameters downstream of the jet injection and 3-5 jet diameters from the bottom wall.
- Peak heat release occurs where local velocity is low and mixture fraction is near stoichiometric. Location of peak heat release is given as along the centerline and just above the CRVP.
- The Takeno flame index[Yamashita et al., 1996], mixture fraction scalar dissipation rate and a topological flow classification[Chong et al., 1990] are given.
- The collocation of high heat release regions with low velocity regions is not conclusive to suggest either a premixed mode of operation or a non-premixed mode, but taken in combination with the observed alignment of fuel and oxidizer gradients in those regions, the likelihood of a premixed flame stabilization mechanism increases.
- Author states that there is "conspicuous interaction between the flame and the flow structures."
- The length scale of flow features grows considerably across the flame.
- The flame is seen to be most diffuse and penetrated by small scale structures near the breakup zone of the jet. Note: How is the breakup zone defined?
- The flame front is the thinnest in regions with continuous block of NSS/U topology. Note: Look at work on flow topology [Chong et al., 1990]

### 4 Multiple Non-Reacting Jets in Crossflow

#### 4.1 Experimental Characterization

4.1.1 Correlation for Temperature Profiles in the Plane of Symmetry Downstream of a Jet Injected Normal to a Crossflow

[Holdeman, 1972]

#### 4.1.2 Mixing of a Row of Jets with a Confined Crossflow

[Holdeman and Walker, 1977]

### 4.1.3 Experimental investigation of opposed jets discharging normally into a cross-stream

[Atkinson et al., 1982]

#### 4.1.4 Experiments in Dilution Jet Mixing

[Holdeman et al., 1984]

#### 4.1.5 Vortex Modeling of Single and Multiple Dilution Jet Mixing in a Cross Flow

[Karagozian et al., 1986]

#### 4.1.6 Lateral Jet Injection into Typical Combustor Flowfields

[Lilley, 1986]

4.1.7 Characteristics of Air Jets Discharging Normally into a Swirling Crossflow

[Ahmed and So, 1987]

#### 4.1.8 Experimental Studies of Combustor Dilution Zone Aerodynamics, Part II: Jet Development

[Stevens and Carrotte, 1990]

#### 4.1.9 Mixing of Multiple Jets with a Confined Subsonic Crossflow

[Holdeman, 1993]

#### 4.1.10 Geometry and Flow Influences on Jet Mixing in a Cylindrical Duct

[Hatch et al., 1995]

#### 4.1.11 Mixing of Multiple Jets with a Confined Subsonic Crossflow: Part I–Cylindrical Duct

[Holdeman et al., 1997a]

#### 4.1.12 Mixing of Multiple Jets with a Confined Subsonic Crossflow Part II–Opposed Rows of Orifices in Rectangular Ducts

[Holdeman et al., 1997b]

#### 4.1.13 Flow Coupling Effects in Jet-in-Crossflow Flowfields

[Bain et al., 1999]

#### 4.1.14 Optimization of Orifice Geometry for Crossflow Mixing of a Cylindrical Duct

[Kroll et al., 2000]

#### 4.1.15 Jet Injection into Swirling Crossflow for Improved Mixing and Combustion

[Lilley, 2002]

# 4.1.16 Surface shear stress measurements around multiple jets in crossflow using the fringe imaging skin friction technique

[Peterson and Plesniak, 2004b]

#### 4.1.17 Noncanonical Short Hole Jets-in-Crossflow for Turbine Film Cooling

[Plesniak, 2006]

#### 4.1.18 Dynamics of Single and Twin Circular Jets in Cross Flow

[Ibrahim and Gutmark, 2006]

#### 4.1.19 Experimental Investigation of the Jets in Crossflow: Nonswirling Flow Case

[Strzelecki et al., 2009]

#### 4.1.20 Impact of the temperature of twin inclined tandem jets on their dynamic interaction with a cooler oncoming crossflow

[Radhouane et al., 2009]

# 4.1.21 Influence of the Geometrical and Gasdynamic Parameters of a Mixer on the Mixing of Radial Jets Colliding with a Crossflow

[Ktalkherman et al., 2010]

#### 4.1.22 Spreadsheet Calculations for Jets in Crossflow: Opposed Rows of Inline and Staggered Holes and Single and Opposed Rows with Alternating Hole Sizes

[Holdeman et al., 2010]

#### 4.1.23 Dynamics of single and twin jets in cross flow

[Gutmark et al., 2010]

Authors use 2-D lowspeed PIV to experimentally study single and "tandem" circular gaseous jets injected into crossflow. The study addresses jet trajectory, penetration, windward and leeward spread, decay rate, shielding effects, so-called "reversed flow region" and kinetic energy of turbulence.

For the tandem cases, penetration of the front jet was found to be comparable to that of a single jet. Turbulent kinetic energy analysis reveals that both the front and rear jet demonstrate the usual low turbulence core with higher turbulence in the shear layer at the jet boundary. The jet core subsequently transitions to high turbulence production as the windward and leeward shear layers coalesce.

The experimental setup utilizes a cold flow wind tunnel seeded with  $3-8\mu m$  olive oil particles. Air density is uniform for the upstream flow and the jet(s). Velocity ratio is held at *three* for all cases. Upstream turbulence intensity is less than 1%. Boundary layer control is accomplished by injecting the transverse jets from a narrow platform elevated above the wind tunnel wall.

Observations include the following:

- Trajectory is identified as the "location of points corresponding to the maximum velocity of the jet." Other researchers have used streamline trajectories to study penetration phenomena. It is known that trajectories generated from the locus of maximum jet velocities rise more quickly than trajectories calculated using the streamline methodology.
- The jet spreads more on the leeward side than on the windward side.
- The mean centerline velocity is maintained in the potential core but diminishes sharply once the jet starts to deflect in the streamwise direction. The CRVP may be responsible for this phenomena as it entrains fluid.
- The mean velocity trajectory of the jets and "zero streamwise velocity" line are plotted on a velocity contour map. It is noted that the reverse flow region is fundamentally three dimensional.
- Jet deflection in the mean flow direction is accompanied by cross-sectional area increases and initial axial velocity of the jet must be redistributed to other x-z planes of the flow channel.
- The strength of the reverse flow region is influenced by the degree of blockage of the freestream by the jet. The upstream flow deceleration rate is coupled to the jet blockage factor and the magnitude of the adverse pressure gradient on the lee side of the jet.
- The tandem jet injection nearly eliminates the "reversed flow region" on the lee side of the rear jet.
- The turbulence intensity in the jet shear layer of a single jet injected into the crossflow is very symmetric. The shear layers can be identified by the twin peaks in turbulence intensity in the jet nearfield.
- The length of the potential core can be defined as the jet trajectory length from the nozzle origin to the location of peak turbulent kinetic energy.

### 4.2 Numerical Methods and Simulations

4.2.1 Reynolds Stress Modeling of Jet and Swirl Interaction Inside a Gas Turbine Combustor

[Tsao and Lin, 1999]

#### 4.2.2 LES of Multiple Jets in Cross-Flow using a Coupled Lattice Boltzmann-Navier-Stokes Solver

[Feiz, 2006]

#### 4.2.3 Large Eddy Simulation of Impinging Jets in a Confined Flow

[Clayton and Jones, 2006]

#### 4.2.4 Large-Eddy simulation of twin impinging jets in cross-flow

[Li et al., 2007]

#### 4.2.5 Mixing of Jets in Cross Flow after Double Rows of Radial Injections

[Nirmolo et al., 2008]

#### 4.2.6 Mixing with Jets in Cross-Flow

[Kandakure et al., 2009]

#### 4.2.7 Study of the Cold Flow Field of a Multi-Injection Combustor

[Wang et al., 2009]

#### 4.2.8 Experimental and Computational Investigations of Flow and Mixing in a Single-Annular Combustor Configuration

[Jakirlić et al., 2009]

### 5 Multiple Reacting Jets in Crossflow

#### 5.1 Empirical Results, Mixing Studies and Pattern Factor Optimization

# 5.1.1 Modification of Combustor Stoichiometry Distribution for Reduced $NO_x$ Emission From Aircraft Engines

[Sturgess et al., 1993]

#### 5.1.2 Effect of Dilution Air on the Scalar Flowfield at Combustor Sector Exit

[Gulati et al., 1995]

#### 5.1.3 Jet Mixing in a Reacting Cylindrical Crossflow

[Leong et al., 1995]

#### 5.1.4 Mixing of Jet Air with a Fuel-Rich, Reacting Crossflow

[Leong et al., 1999]

#### 5.1.5 Optimization of Jet Mixing into a Rich, Reacting Crossflow

[Leong et al., 2000]

#### 5.1.6 The Combustion Efficiency of Enclosed Waste Gas Flares: A Study of Jet Mixing in a Reacting Cross-Flow

[Popovic et al., 2000]

5.1.7 The Effect of Jet Mixing on the Combustion Efficiency of a Hot Fuel-Rich Cross-Flow

[Boutazakhti et al., 2001]

#### 5.1.8 The Effect of Jet Mixing on the Combustion Efficiency of a Hot, Fuel-Rich Cross-Flow

[Boutazakhti, 2000]

#### 5.1.9 Low Emissions RQL Flametube Combustor Test Results

[Chang and Holdeman, 2001]

#### 5.1.10 Assessing Jet-Induced Spatial Mixing in a Rich, Reacting Crossflow

[Demayo et al., 2003]

5.1.11 The Effects of Air Preheat and Number of Orifices on Flow and Emissions in an RQL Mixing Section

[Holdeman and Chang, 2007]

# 5.1.12 Control of Heat Release and NO Emissions in a Combustor Through Modulation of Transverse Air Jets

[Tuncer et al., 2007]

#### 5.1.13 Combustion in a cross flow with air jet nozzles

[Kamal, 2009]

#### 5.1.14 Influence of the Primary Jets and Fuel Injection on the Aerodynamics of a Prototype Annular Gas Turbine Combustor Sector

[Mohammad et al., 2011]

#### 5.2 Numerical Methods and Simulations

5.2.1 Evaluation of mixing and chemical reactions within a jet in crossflow by means of LES

[Denev et al., 2005]

### 5.2.2 Large-Eddy Simulation of Realistic Gas Turbine Combustors

[Moin and Apte, 2006]

# 5.2.3 Large-eddy simulation analysis of turbulent combustion in a gas turbine engine combustor

[You et al., 2008]

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