SHEAR LAYER INSTABILITIES IN VARIABLE DENSITY TRANSVERSE JETS

Daniel Getsinger[*], Levon Gevorkyan[*], Cory Hendrickson[*], Owen I. Smith[*], and Ann R. Karagozian[*a)]
[*]*Department of Mechanical and Aerospace Engineering*
UCLA Henry Samueli School of Engineering and Applied Science
Los Angeles, CA 90095-1597, USA

Summary This experimental study explores upstream shear layer instabilities associated with the gaseous low density jet in crossflow or transverse jet. Different experimental diagnostic methods are employed here, including simultaneous Planar Laser-Induced Fluorescence (PLIF) imaging of acetone seeded in the jet and stereo (3D) Particle Image Velocimetry (PIV). These studies, together with hotwire anemometry, provide substantial evidence for the upstream jet shear layer's transition from convective to absolute instability as the jet-to-crossflow momentum flux ratio J and/or the jet-to-crossflow density ratio S are brought below critical values. Alterations in the transverse jet structure as well as mixing characteristics are quantified, as are alterations in the jet's response to different modes of external jet forcing. These studies provide clear mechanisms for the control of transverse jet behaviour based on requirements for altered penetration, spread, and mixing.

BACKGROUND AND CONTEXT OF PRESENT STUDIES

The jet injected normally into crossflow[1,2] or transverse jet is a flowfield that has extensive applications, particularly in energy generation and propulsion engines[3], with superior nearfield mixing characteristics when compared with the free jet issuing into quiescent surroundings[4,5]. While the free jet injected into fluid of the same density is typically considered to be a convectively unstable flow, where disturbances initiated within the jet evolve and grow downstream[6], when the free jet density is reduced below a critical fraction of the surrounding fluid's density, the shear layer is known to become absolutely unstable. Absolutely unstable flows are such that a disturbance initiated within the flow will grow not only in space but also in time at or near the location of the disturbance, allowing for wholesale oscillations to take over the flow, such that it becomes self-excited and global in nature.

There is a growing body of evidence that the equidensity jet in crossflow becomes absolutely or globally unstable when the jet-to-crossflow velocity ratio R lies below a critical value[2,7,8,9]. Our earlier gas-phase experimental studies for a nitrogen jet emanating from a flush nozzle into a uniform crossflow of air demonstrate that, for fixed jet Reynolds numbers, as the crossflow magnitude is increased, the spectral character of the upstream shear layer instability is substantially altered. As R is reduced from infinity (the free jet), shear layer instabilities are initiated closer to the jet orifice and are strengthened, with evidence of subharmonic and higher harmonic formation and energy transfer from fundamental to subharmonic modes. When R is reduced below approximately 3.2, the shear layer becomes globally unstable or self-excited; evidence[7,9] for this transition includes the initiation of strong single-tone disturbances that do not vary along the jet's shear layer, the inhibition of subharmonic initiation, lock-in to applied frequencies only at very large forcing amplitudes and/or at frequencies close to the fundamental, and evidence of a Hopf bifurcation. The nature of the transition in transverse jet shear layer instabilities may be used to employ strategies for the active control of such jets[10].

The aim of the present studies is to examine the nature of such instabilities in low density jets in crossflow, to determine the sensitivities of the transition to flow conditions, and in particular to quantify differences in jet flow structure (jet penetration, spread, downstream mixing, shear layer vorticity generation, etc.) that would enable optimized performance for a range of engineering applications.

EXPERIMENTAL APPROACH AND SAMPLE RESULTS

These transverse jet experiments are performed in a low speed wind tunnel, primarily utilizing two non-intrusive optical diagnostics: PLIF of seeded acetone, and stereo (3D) PIV. The excitation source for both PLIF and PIV is a dual cavity Q-switched Nd:YAG laser (Litron Nano L PIV), which is equipped with both second and fourth harmonic generation for simultaneous collinear output at 532 nm and 266 nm. Mixtures of helium and nitrogen, seeded with acetone vapor and/or DEHS oil particles for PLIF and PIV, respectively, are injected through a nozzle mounted flush with the bottom wall of the wind tunnel test section, issuing at room temperature into a crossflow of air. Hot wire anemometry is also used to quantify the spectral character of the evolution of the upstream shear layer, as done in equidensity studies. Flow controllers and a specially designed mixer provide the ability to vary both jet-to-crossflow density ratio S as well as jet-to-crossflow momentum flux ratio J; for the equidensity transverse jet, J reduces to R^2.

These experiments have revealed new phenomena, whereby a transition from convective to absolutely unstable shear layers for the transverse jet is observed to be dependent on both S and J. The process of "lock-in" is particularly

[a)] Corresponding author. Email: ark@seas.ucla.edu.

interesting here, where the amplitudes and jet forcing frequencies for which the jet locks in to the forcing condition occupy a much broader range of operating conditions for higher momentum flux ratio jets than for lower momentum flux ratios[11]. The jet appears to undergo a transition to global instability as J is brought below a value of approximately 10. At low enough momentum flux ratios, the vortex pairing process is completely inhibited in the near field, up to 5 jet diameters along the shear layer. Interestingly, this process of energy transfer from the fundamental mode to its subharmonic appears to be enhanced at lower density ratios, a result which was not expected in consideration of the known transition to global instability in the low density free jet (which occurs below a critical value of S).

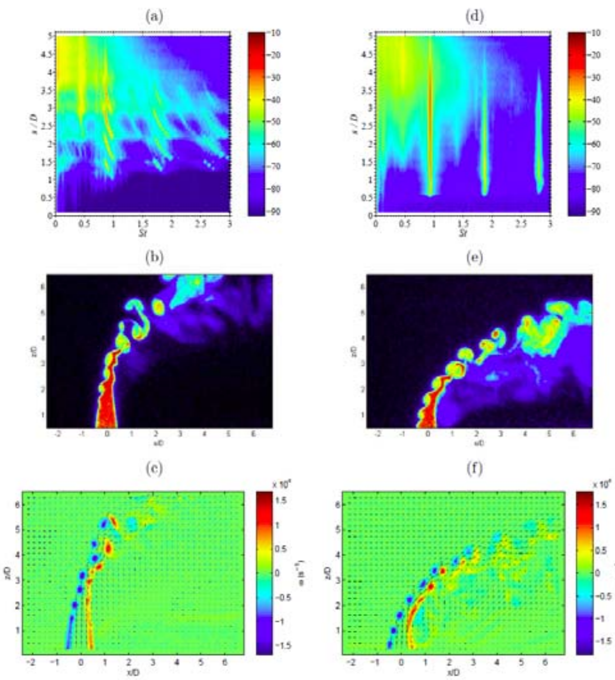

Figure 1. Measurements for transverse jets with S = 1:00, J ~ 20 (left) and J ~ 8 (right). (a,d): Hotwire spectra along the upstream shear layer, where the colormap represents spectral magnitude (in dB), plotted vs. Strouhal number St = fD/Uj at various spatial locations s/D. (b,e): Instantaneous centerplane jet concentration fields acquired via acetone PLIF. (c,f): Instantaneous centerplane velocity and vorticity fields from 3D PIV results. Data in (b) & (c), (e) & (f) are taken simultaneously.

Non-intrusive simultaneous acetone PLIF and stereo PIV diagnostics reveal vorticity generation and flow evolution that are consistent with quantification of shear layer instabilities via hot wire anemometry. Sample comparisons among spectral characteristics, jet concentration fields, and 3D PIV velocity and vorticity fields for the transverse jet are shown in Figure 1. Data in the left column correspond to an approximate jet-to-crossflow momentum flux ratio J of 20, representing convectively unstable shear layer behaviour with initiation of instabilities beyond one jet diameter from the jet exit plane. In contrast, data in the right-hand column correspond to J approximately equal to 8, well below the condition for generation of an absolutely unstable shear layer, with evidence of nearly immediate initiation of the strong global instability. Enhanced generation of downstream wake vorticity and coupling of these structures to wall boundary layer fluid is observed at lower momentum flux ratios, consistent with alterations in jet mixing and spread. Additional experiments at a range of alternative flow conditions reveal similar differences in flow and vorticity evolution between convective and absolute instability conditions.

The present experiments also explore low density transverse jet behaviour during acoustical excitation of jet fluid, via closed loop control which enables accurate shaping of the temporal waveform at the jet exit. Comparisons are made between the effects of sinusoidal excitation and square wave excitation for different duty cycles. Square wave forcing at specific “optimal” duty cycles is observed to create maximum overall jet spread, although there is not always direct correspondence among maximal jet spread, enhanced centreline concentration decay, and minimal jet mixing length, especially for conditions of globally unstable transverse jet behaviour. The results of these detailed examinations provide a potential rubric by which control of such jet flows may be designed for a range of technological applications.

References

[1] Kelso, R. M., Lim, T. T., and Perry, A. E., “An experimental study of round jets in cross-flow”, **J. Fluid Mech., 306**, pp. 111-144, 1996.
[2] Karagozian, A.R., “Transverse jets and their control”, **Prog. Energy Comb. Science** 36(5), pp. 531–553, 2010.
[3] Margason, R.J., “Fifty Years of Jet in Cross Flow Research.” *AGARD-CP-534*, Vol. 1, 1993, pp. 1-141.
[4] Broadwell, J.E. and Breidenthal, R.E., “Structure and mixing of a transverse jet in incompressible flow,” **J. Fluid Mech.**, **148**, pp. 405-412, 1984.
[5] Karagozian, A. R. “An analytical model for the vorticity associated with a transverse jet.” **AIAA Journal**. **24**, pp. 429-436, 1986.
[6] Huerre, P. & Monkewitz, P. A., “Local and global instabilities in spatially developing flows”, **Ann. Rev. Fluid Mechanics 22**, 473–537, 1990.
[7] Megerian, S., Davitian, J., Alves, L. S. de B., and Karagozian, A. R., “Transverse Jet Shear Layer Instabilities. Part I: Experimental Studies.”, **J. Fluid Mech**, **593**:93–129, 2007.
[8] Bagheri, S., Schlatter, P., Schmid, P.J., Henningson, D.S., “Global stability of a jet in crossflow” **J. Fluid Mech**; **624**:33–44, 2009
[9] Davitian, J., Getsinger, D., Hendrickson, C., and Karagozian, A. R., “Transition to Global Instability in Transverse Jet Shear Layers”, **J. Fluid Mech., 661**, pp. 294-315, 2010.
[10] Davitian, J., Hendrickson, C., Getsinger, D., M’Closkey, R. T., and Karagozian, A. R., “Strategic Control of Transverse Jet Shear Layer Instabilities”, **AIAA Journal**, **48 (9),** pp. 2145-2156, 2010.
[11] Getsinger, D., Hendrickson, C., and Karagozian, A. R., “Transition to Self-Excited Oscillations in Low Density Transverse Jet Shear Layers”, AIAA 2011-40, January, 2011.