Experimental investigation of nozzle aspect ratio effects on underexpanded hydrogen jet release characteristics

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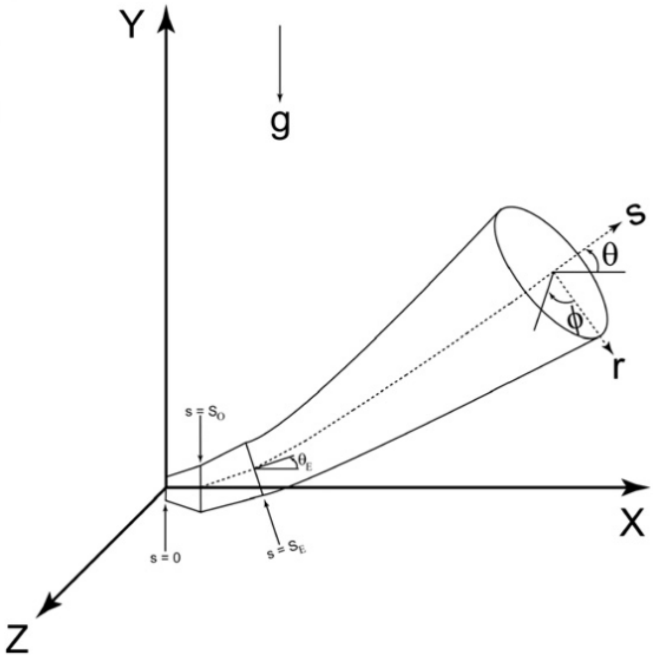
Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000

Circular free-jets have been well-characterized by simple integral models that invoke self-similarity



Reichardt, *VDI-Forschungsheft*, 1942

Jirka, *Environ Fluid Mech*, 2004
Houf & Schefer, *IJHE*, 2008
Xiao et al., Sci Tech Nuclear Installations, 2009
Winters & Houf, *IJHE*, 2010

Mass $$\frac{\partial}{\partial S}\int_0^{2\pi}\int_0^{\infty}\rho V r dr d\phi = \rho_{amb} E$$

x-Mom $$\frac{\partial}{\partial S}\int_0^{2\pi}\int_0^{\infty}\rho V^2 \cos\theta \, r dr \, d\phi = 0$$

y-Mom $$\frac{\partial}{\partial S}\int_0^{2\pi}\int_0^{\infty}\rho V^2 \sin\theta \, r dr d\phi = \int_0^{2\pi}\int_0^{\infty}(\rho_{amb}-\rho) g r dr d\phi$$

Species $$\frac{\partial}{\partial S}\int_0^{2\pi}\int_0^{\infty}\rho V Y r dr d\phi = 0$$

Energy $$\frac{\partial}{\partial S}\int_0^{2\pi}\int_0^{\infty}\rho V (h - h_{amb}) r dr d\phi = 0$$

Gaussian velocity, concentration, & excess state variable profiles

$$\frac{V}{V_{CL}} = \exp\left(-\frac{r^2}{B^2}\right)$$

B: velocity jet width
λ: concentration-to-velocity jet width ratio
X: excess state variable

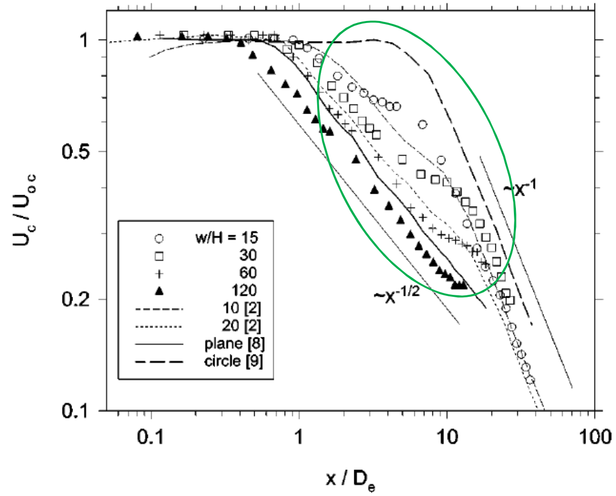
$$\frac{\rho Y}{\rho_{CL} Y_{CL}} = \exp\left(-\frac{r^2}{\lambda^2 B^2}\right)$$

$$\frac{X - X_{amb}}{X_{CL} - X_{amb}} = \exp\left(-\frac{r^2}{\lambda^2 B^2}\right)$$

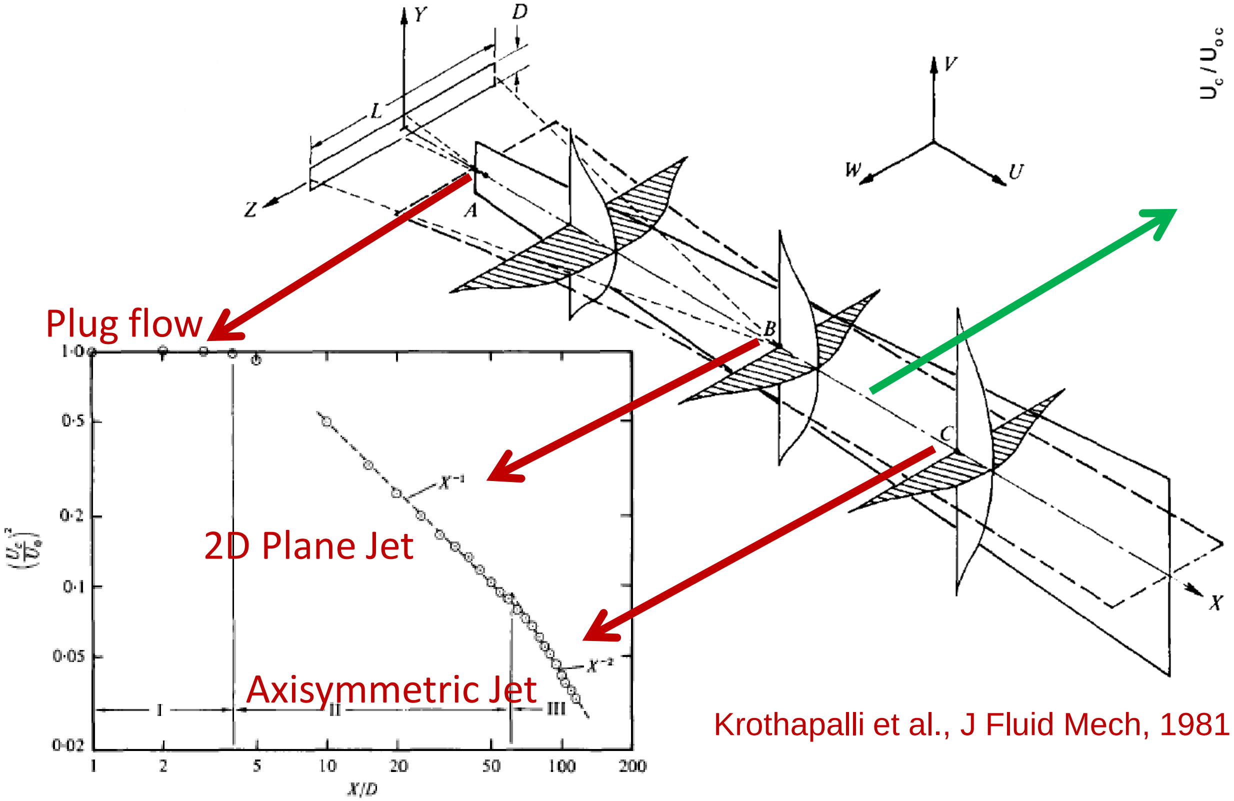
Velocity & concentration profiles have linear inverse decay rates

Unchoked slot jets have likewise been thoroughly investigated

Mi et al., Phys Fluids, 2005



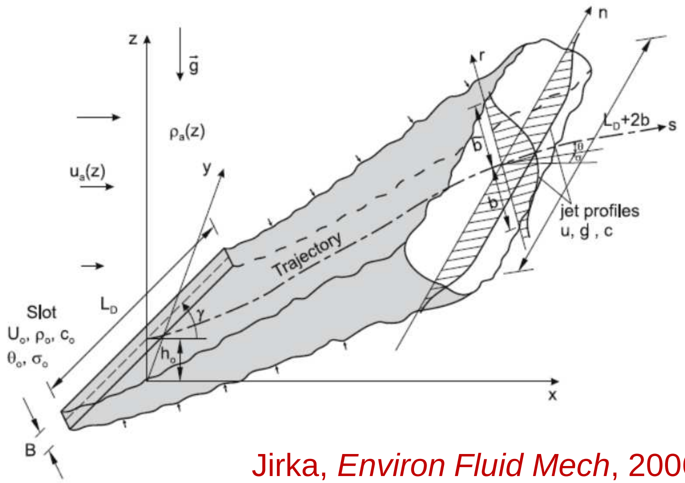
Transition region between planar & axisymmetric regions



Krothapalli et al., J Fluid Mech, 1981

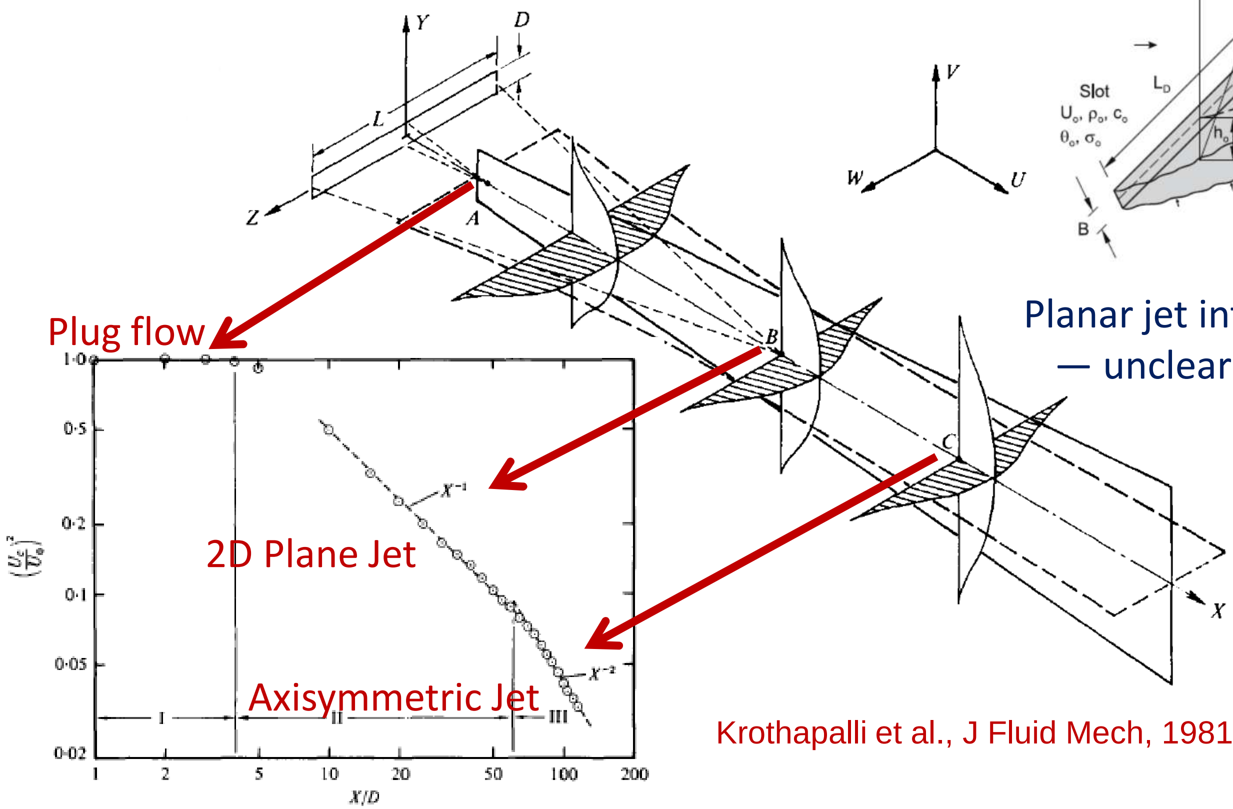
Distinct 2D region with inverse ½ power centerline decay rate exists

Unchoked slot jets have likewise been thoroughly investigated



Jirka, *Environ Fluid Mech*, 2006

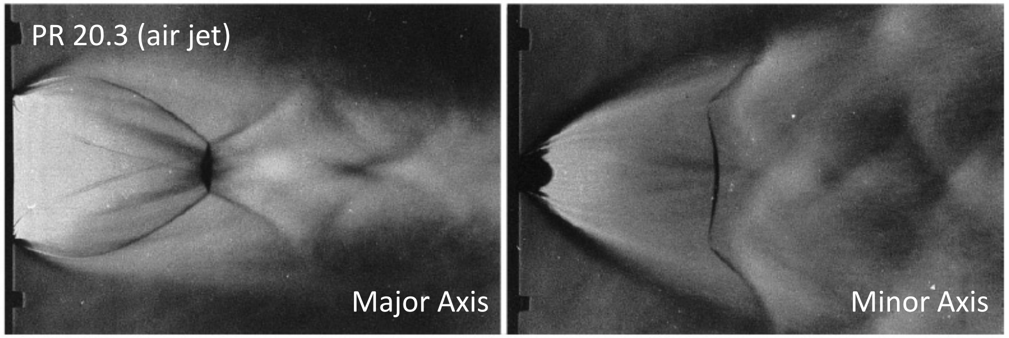
Planar jet integral model has been developed — unclear if applicable to choked slot jets



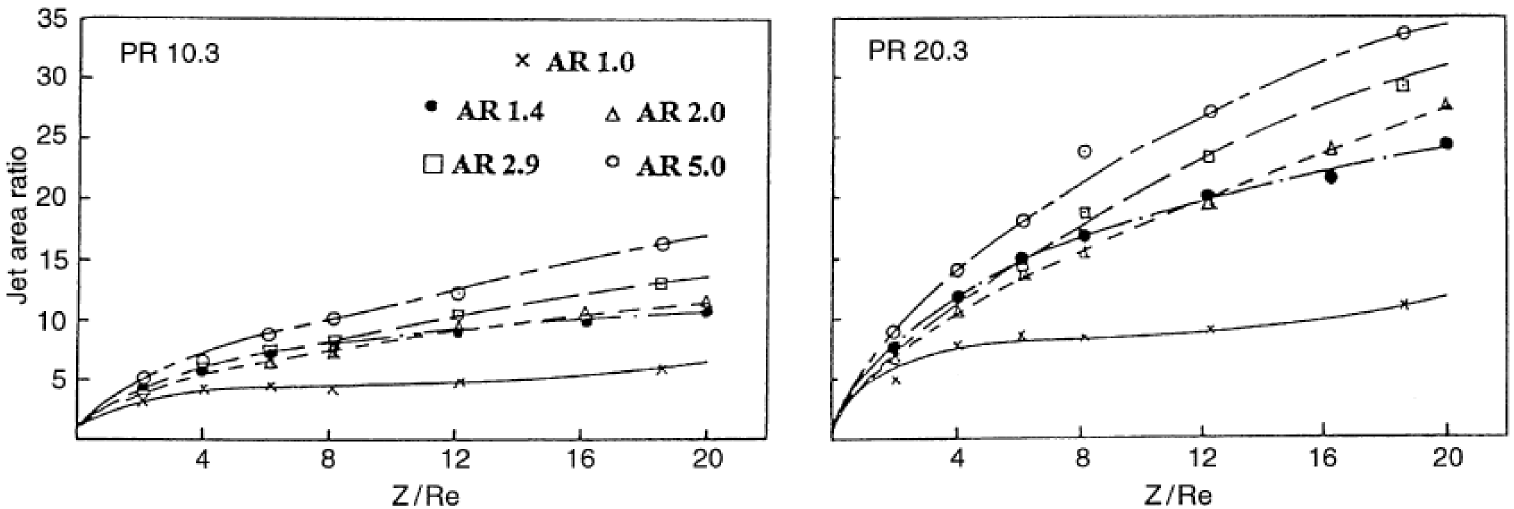
Krothapalli et al., J Fluid Mech, 1981

Distinct 2D region with inverse ½ power centerline decay rate exists

Many leaks are non-circular: e.g., cracks, leaky fittings, ruptures



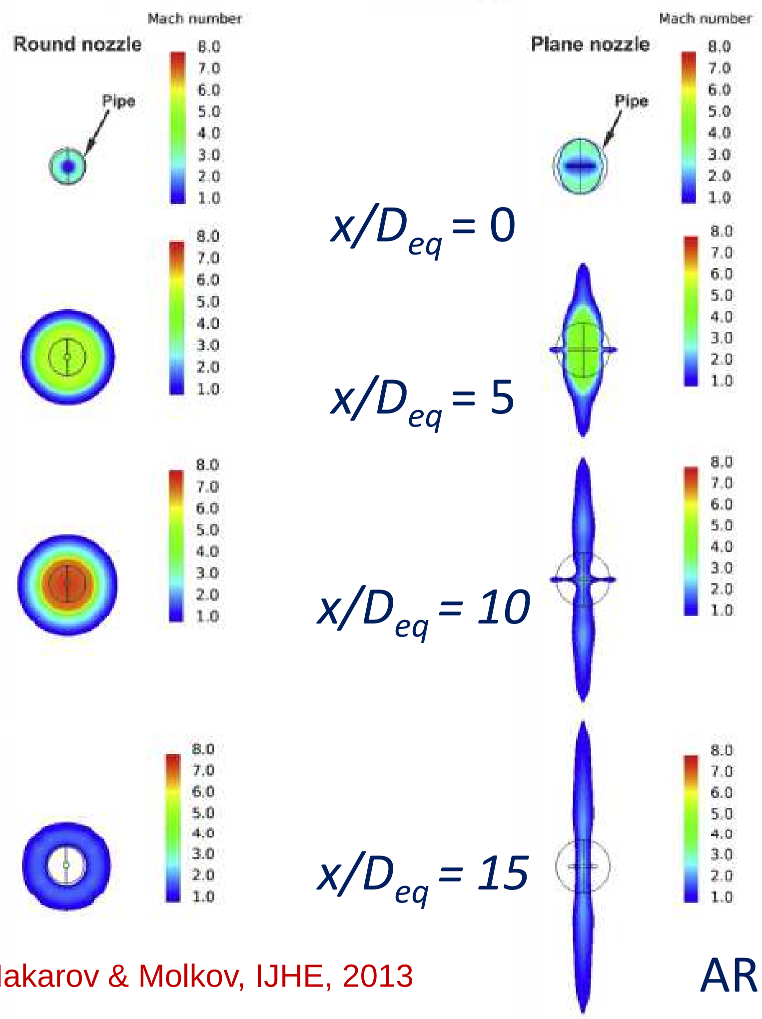
Rajakuperan & Ramaswamy, *Exp in Fluids*, 1998



Elevated near field jet area ratios result in faster initial concentration decay rates

Axis switching due to faster minor axis jet spreading rates observed

Axis switching phenomena observed for simulations of choked hydrogen slot jets



$x/D_{eq} = 0$

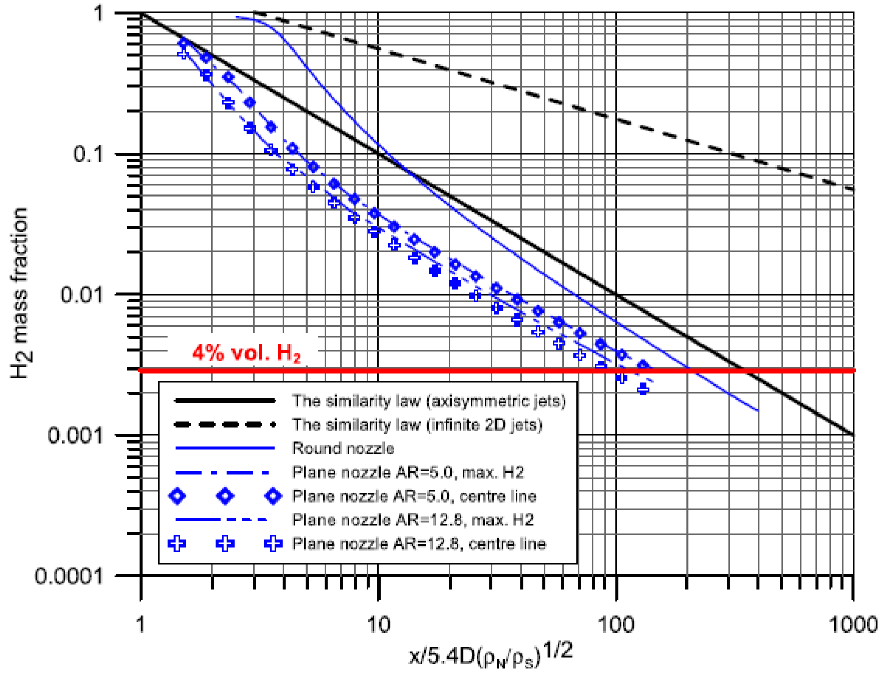
$x/D_{eq} = 5$

$x/D_{eq} = 10$

$x/D_{eq} = 15$

D_{eq} = 1.0 mm

p_0 = 40 MPa

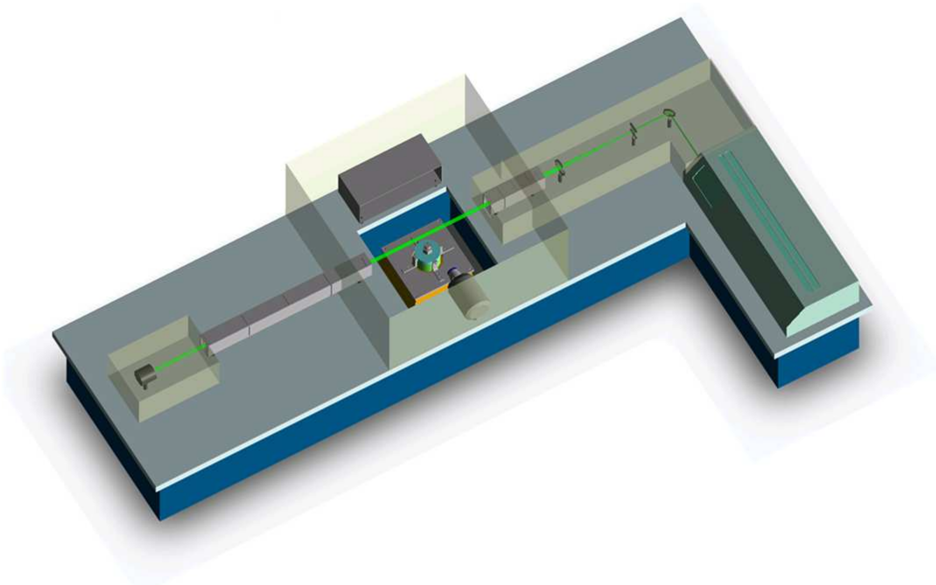


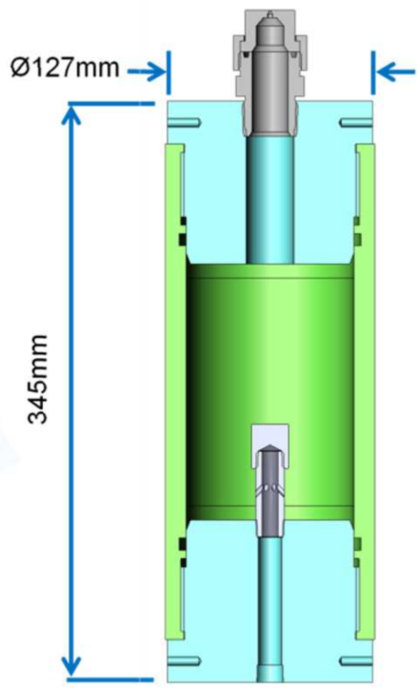
Makarov & Molkov, IJHE, 2013

AR = 12.8

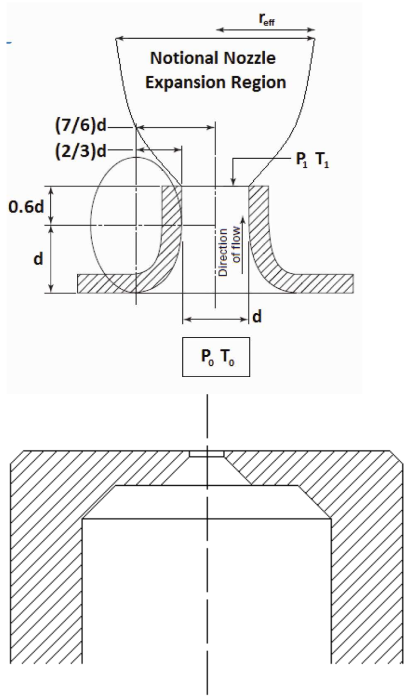
Faster slot jet centerline decay rates due to increased area available for entrainment

Downstream scalar field examined via high-resolution Planar Rayleigh Scatter Imaging (PLRS)





D_{eq} = 1.5 mm
p_0 = 10 bar



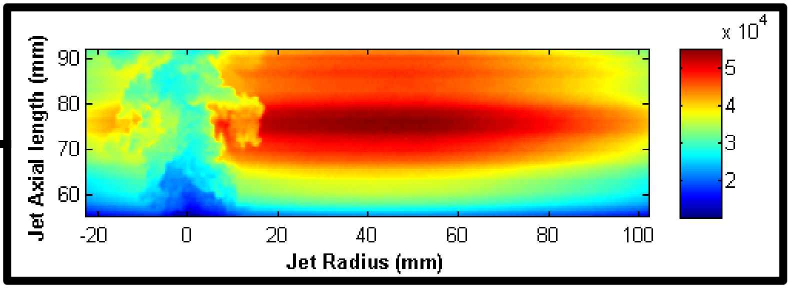
AR = 1, 2, 4, & 8

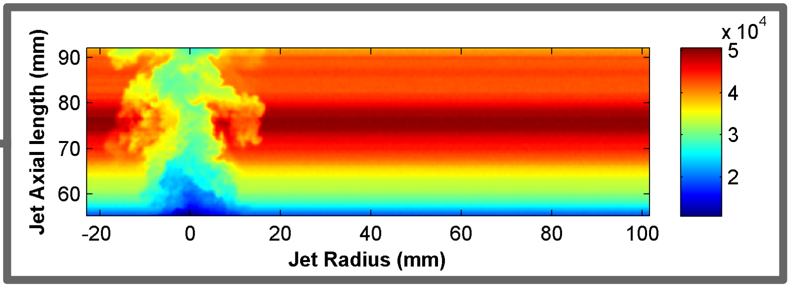
Schlieren imaging also performed to provide a qualitative description of the underexpanded jet exit shock structure

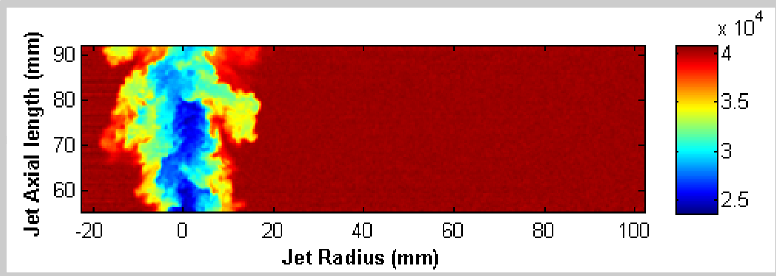
Signal intensity corrections used to create quantitative concentration image

R:	Raw image
E_B:	Electronic bias
B_G:	Background luminosity
p_F:	Laser power fluctuation
O_R:	Camera/lens optical response
S_B:	Background scatter
S_t:	Laser sheet profile variation
I:	Corrected intensity

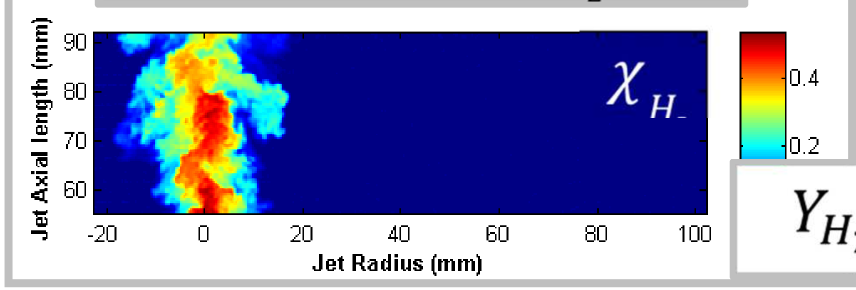
$$R = \boxed{p_F \cdot O_R \cdot \boxed{(\boxed{I} \cdot S_t} + S_B)} + E_B + B_G$$



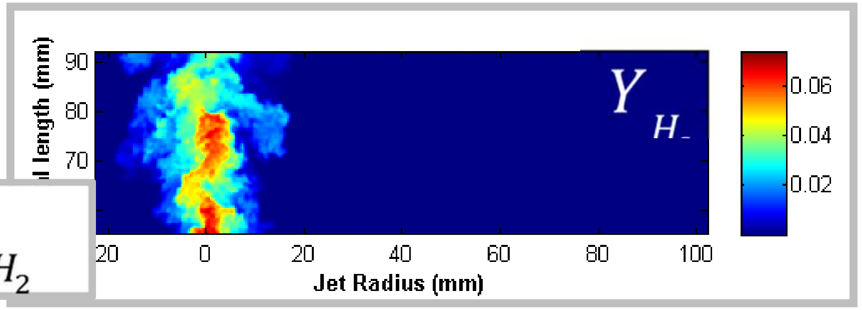




Mole Fraction $\chi_{H_2} \propto I$

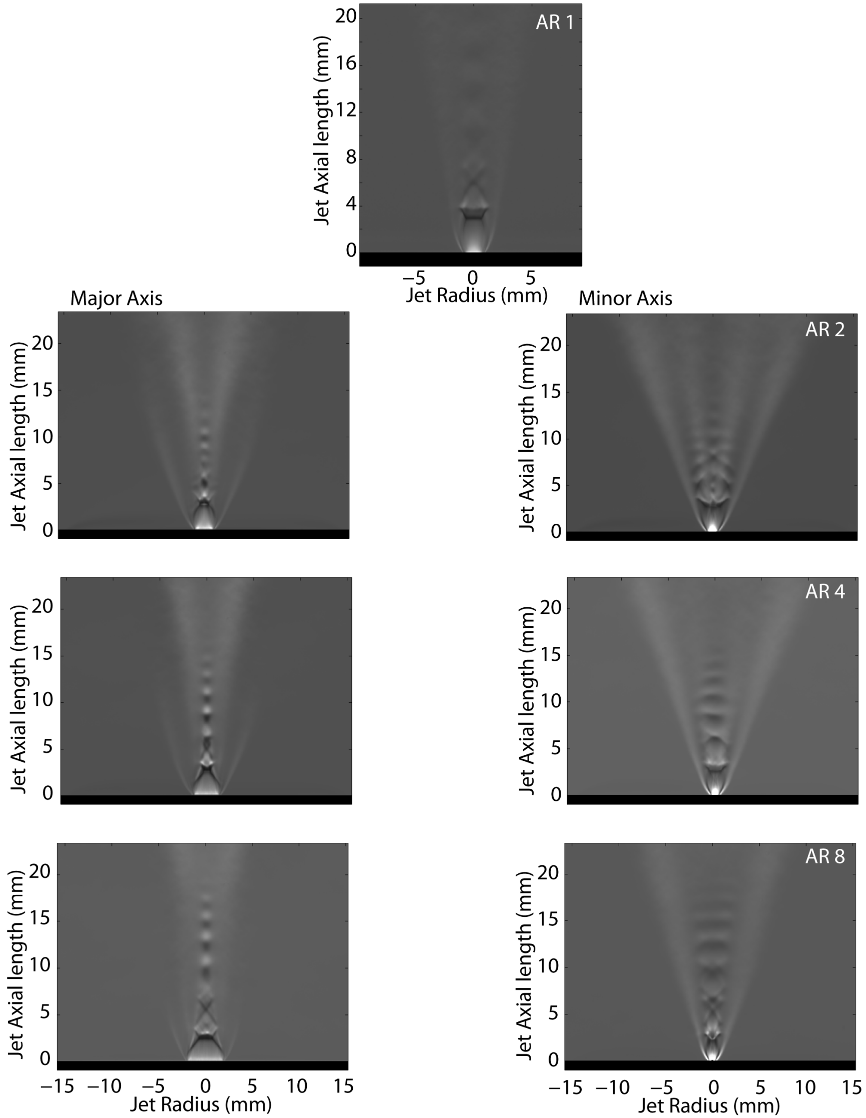


$Y_{H_2} \propto \chi_{H_2}$



Similar corrections performed for schlieren images

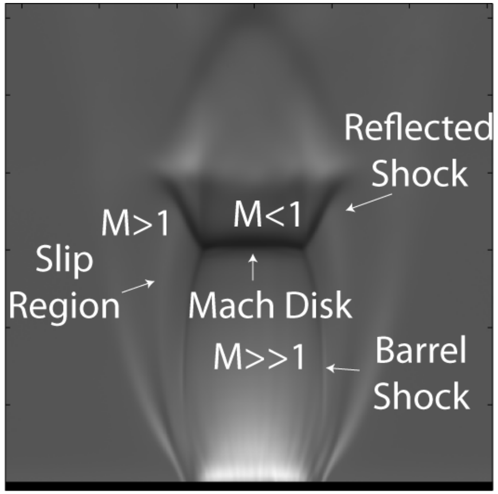
Schlieren images indicate initial jet spreading rates are fastest along the minor axis



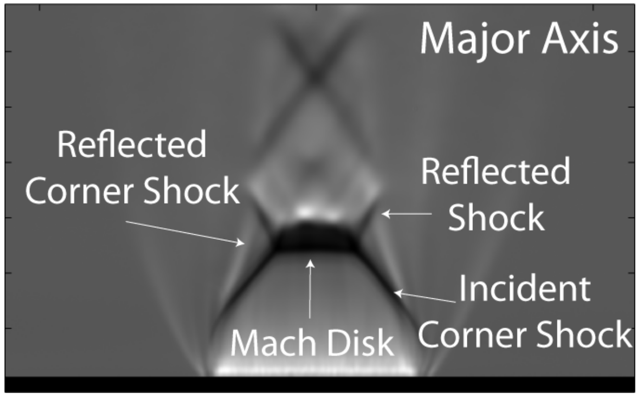
Downstream oblique shock structure disappears ~12-17 mm downstream

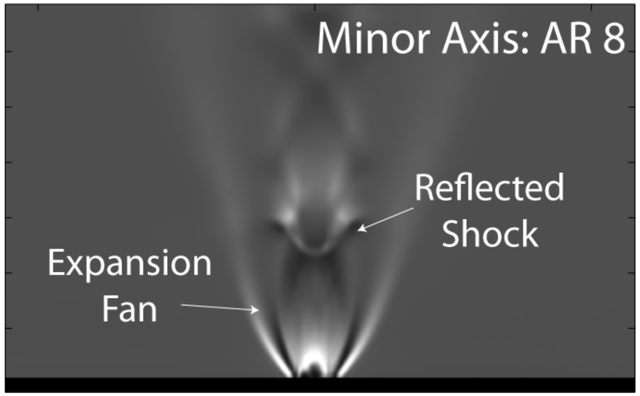
D_{eq} = 1.5 mm
p_0 = 10 bar

Close-up schlieren imaging reveals unique slot nozzle behavior



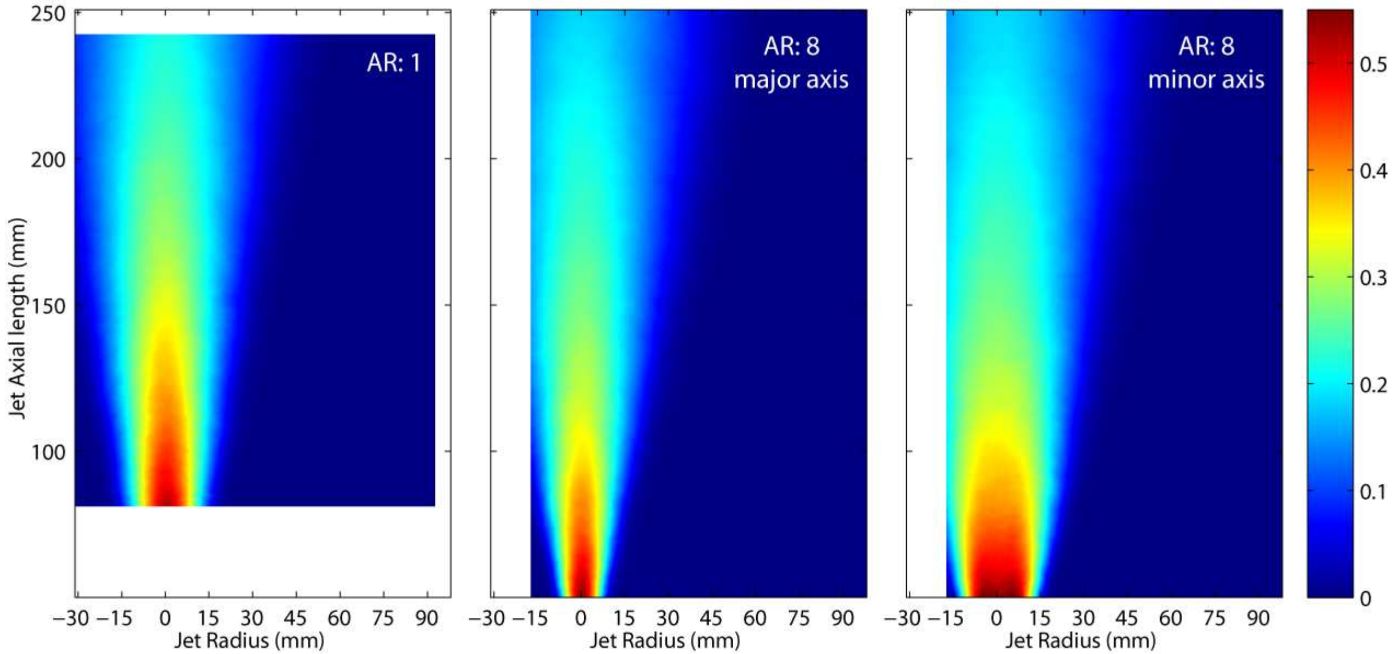
Strong, sharply converging incident corner shock is missing from the minor axis plane





Unclear if existing choked flows notional nozzle models are applicable

Mean mass fraction slot jet contours confirm axis switching in the scalar field



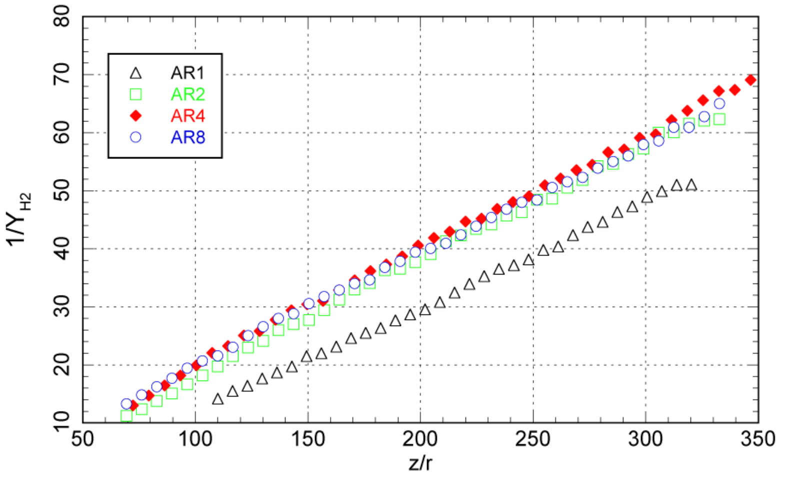
Elevated downstream mass fraction contours for the axisymmetric jet

D_{eq} = 1.5 mm
p_0 = 10 bar

Concentration decay rates remained relatively linear throughout the measurement region

Planar decay region (half-power) not observed

- Upstream of interrogation region?



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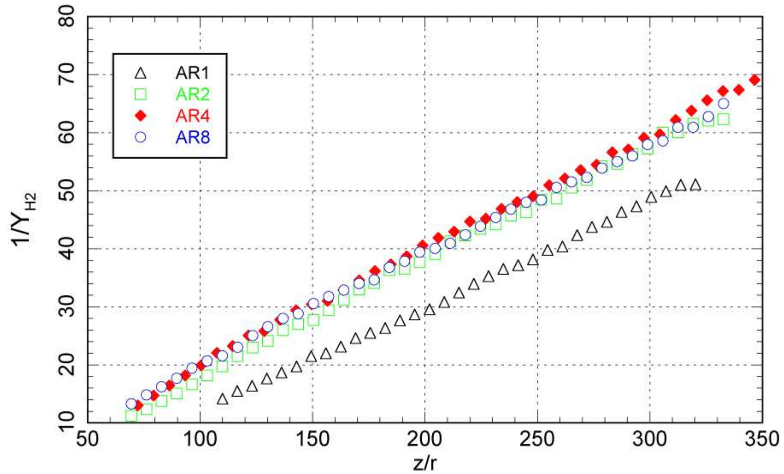
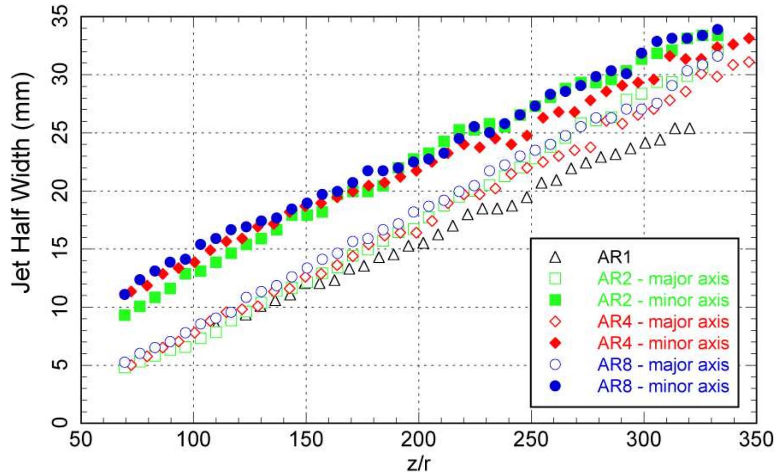




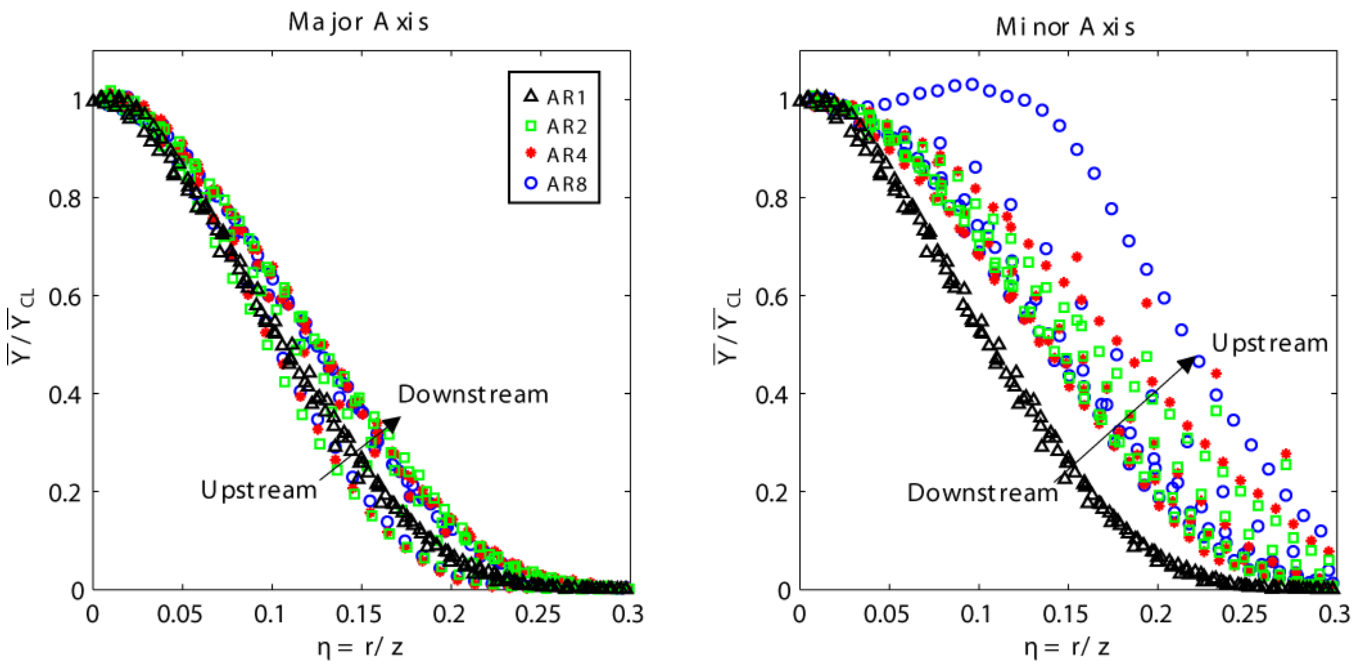
Major & minor axis jet half widths appear to converge

- Half widths larger than for corresponding axisymmetric jet
- Slightly non-linear growth rates – unclear when convergence occurs

Normalized concentration radial profiles along the major/minor axes do not collapse

Axisymmetric profiles collapsed to uniform curves as expected

Normalized profiles grew ***wider along the major axis*** and ***narrower along the minor axis***



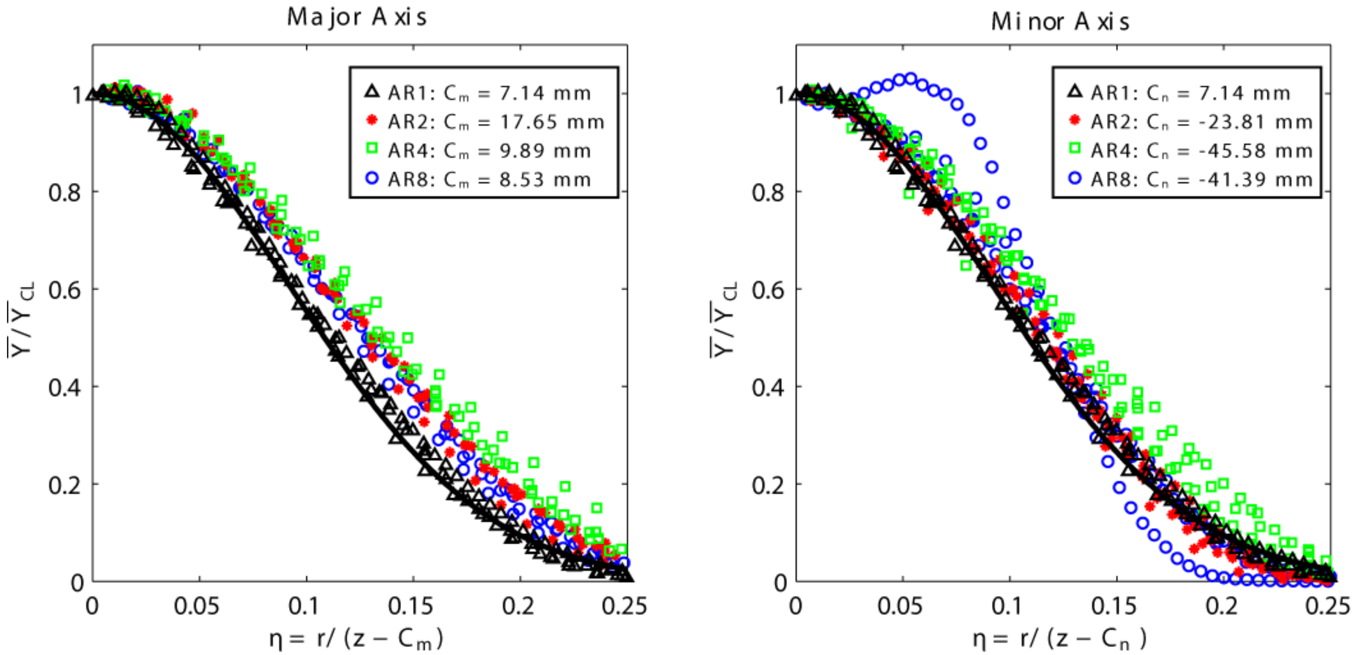
z/D$_{eq}$ = 35, 69, 102, 136, & 161

Minor axis peak H_2 ***near-field*** concentrations observed away from the centerline – not predicted by planar integral models

Virtual coordinates used to provide a best fit collapse to uniform profiles along both axes

Self-similar collapse observed outside of the near-field

Profiles deviated from axisymmetric values – possibly due to strong co-flows required for lab safety



z/D_{eq} = 35, 69, 102, 136, & 161

Results suggest slot jet integral models can be adapted for choked flows — more work still needed

Summary:

Schlieren images indicate faster minor axis initial jet spreading rates

- Likely due to absence of sharply converging incident corner shock

Axis switching confirmed in the scalar measurements

- 2D half-power decay region not observed — possibly upstream of interrogation region
- Slight non-linear growth rates along major/minor axes — appear to converge outside of interrogation region

Near-field normalized mean concentration radial profiles do not collapse to uniform curves along the major/minor axes

- Profiles grew wider along major axis and narrower along minor axis
- Peak H_2 near-field minor axis concentrations observed away from the centerline
- With use of a virtual origin, far-field profiles collapsed to non-Gaussian profiles

Limited results suggest it should be possible to employ slot jet integral models — more research needed to confirm trends

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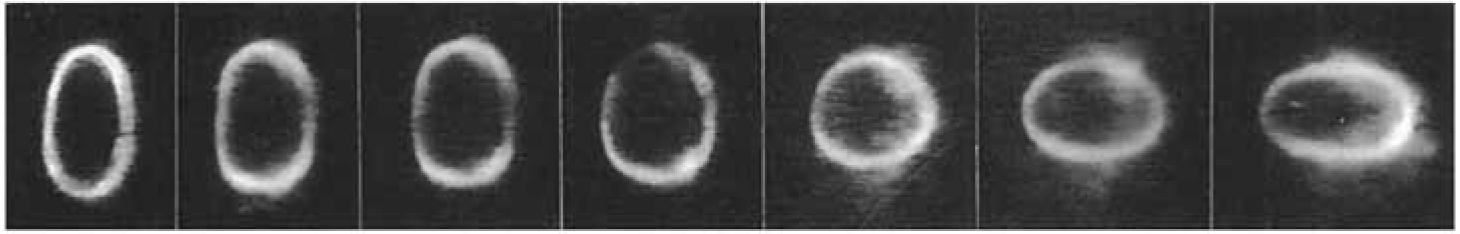
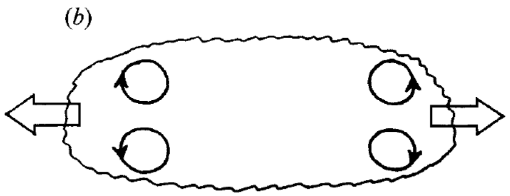
Axis switching phenomena has been observed for unchoked slot jets

Deformation and reorientation of rolled-up azimuthal vortices

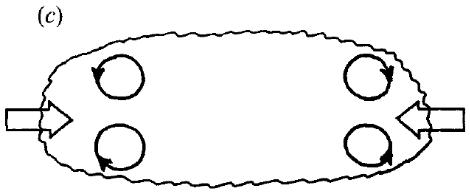


Hussain, *J Fluid Mech*, 1989

Induced streamwise vortex pairs



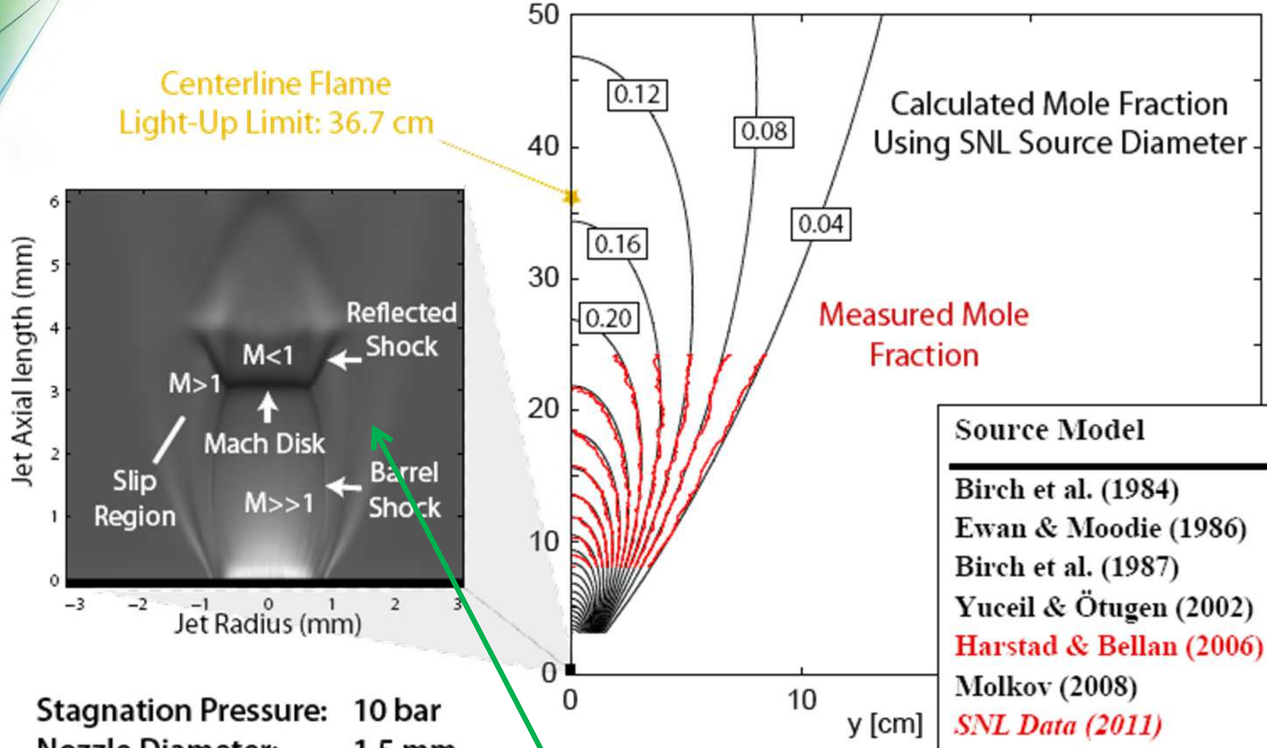
No axis switching



Axis switching

Zaman, *J Fluid Mech*, 1996

Computed & measured mole fraction statistics agree if measured d^* is used as the scaling parameter



Stagnation Pressure: 10 bar
Nozzle Diameter: 1.5 mm

Source Model	d^* [mm]
Birch et al. (1984)	0.947
Ewan & Moodie (1986)	0.993
Birch et al. (1987)	0.790
Yuceil & Ötugen (2002)	0.790
Harstad & Bellan (2006)	1.440
Molkov (2008)	0.993
SNL Data (2011)	*0.867*

Ruggles & Ekoto, *IJHE*, 2012

$$d^* = d_{eff}\sqrt{\rho_{eff}/\rho_\infty}$$

Notional nozzle model outputs

Poor d^* prediction from all models

Most fluid appears to be in the slip region

All models updated w/ Abel-Noble EOS

$$p = Z\rho RH_2T;\ Z = (1 - b\rho)^{-1}$$

- Works well at ambient *T*
- Cryogenic states (T<100 K) poorly predicted

Unclear if equivalent diameters can be used for slot nozzles