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

Adam Ruggles
Isaac Ekoto (presenting)
Sandia National Laboratories

International Conference on Hydrogen Safety
Sept 9, 2013
Circular free-jets have been well-characterized by simple integral models that invoke self-similarity.

Velocity & concentration profiles have linear inverse decay rates.

Gaussian velocity, concentration, & excess state variable profiles

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

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

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

- B: velocity jet width
- \( \lambda \): concentration-to-velocity jet width ratio
- X: excess state variable
Unchoked slot jets have likewise been thoroughly investigated. Transition region between planar & axisymmetric regions.

Distinct 2D region with inverse $\frac{1}{2}$ power centerline decay rate exists.
Unchoked slot jets have likewise been thoroughly investigated.

Plug flow

2D Plane Jet

Axisymmetric Jet

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

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

Jirka, Environ Fluid Mech, 2006

Krothapalli et al., J Fluid Mech, 1981
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

$x/D_{eq} = 0$

$x/D_{eq} = 5$

$x/D_{eq} = 10$

$x/D_{eq} = 15$

$D_{eq} = 1.0 \text{ mm}$

$p_0 = 40 \text{ MPa}$

$AR = 12.8$

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

Makarov & Molkov, IJHE, 2013
Downstream scalar field examined via high-resolution Planar Rayleigh Scatter Imaging (PLRS)

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

$D_{eq} = 1.5 \text{ mm}$

$p_0 = 10 \text{ bar}$

$AR = 1, 2, 4, \& 8$
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

\[ R = p_F \cdot O_R \cdot (I \cdot S_t + S_B) + E_B + B_G \]

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.

\[ D_{eq} = 1.5 \text{ mm} \]
\[ p_0 = 10 \text{ bar} \]
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

\[ D_{eq} = 1.5 \text{ mm} \]
\[ p_0 = 10 \text{ bar} \]
Concentration decay rates remained relatively linear throughout the measurement region.

Planar decay region (half-power) not observed
- Upstream of interrogation region?
Concentration decay rates remained relatively linear throughout the measurement region.

Planar decay region (half-power) not observed
- Upstream of interrogation region?

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*

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

Adam Ruggles
Isaac Ekoto (presenting)
Sandia National Laboratories

International Conference on Hydrogen Safety
Sept 9, 2013

This presentation does not contain any proprietary, confidential, or otherwise restricted information

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
Axis switching phenomena has been observed for unchoked slot jets

Deformation and reorientation of rolled-up azimuthal vortices


Induced streamwise vortex pairs

No axis switching

Axis switching

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

Most fluid appears to be in the slip region

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

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

Notional nozzle model outputs

Unclear if equivalent diameters can be used for slot nozzles

All models updated w/ Abel-Noble EOS

$$p = Z p R H_2 T; \ Z = (1 - b \rho)^{-1}$$

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

Ruggles & Ekoto, *IJHE*, 2012