Measurements of Flow Velocity and Scalar Concentration in Turbulent Multi-Component Jets
7th ICHS

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Introduction

Past work

Figure: Turbulent round CO$_2$ jet ($Ma_c = 0.6$) [De Gregorio 2014].

- Round (axisymmetric) and non-circular (asymmetric) jets through flat surfaces.
- Turbulent and compressible (high $Re$, $Ma \to 1$).
Introduction

Past work, Round jets through flat surfaces (axisymmetric)

- Initial flow condition can significantly influence jet evolution [Nathan et al. 2006].

**Figure:** Radial profiles of mean velocity (U) obtained at x/D=0.05 for contoured, orifice plate, and pipe nozzles [Mi et al. 2001].
Introduction

Past work

Effect of nozzle geometry

- Asymmetric behavior lead to increase in mixing, turbulence intensity, and entrainment rates compared to round jets. [Mi et al 2010, Zaman et al 1999]

Buoyancy effect

- Pure vertical jets reach the self-similarity regime slower than plumes. [Carazzo et al. 2006].
- Horizontal jets scale according to jet momentum to buoyancy generated momentum ratio. [Ash 2012].

Realistic pipe leaks not yet considered.
Introduction

Current study

- 1/4 in pipe with $D = 2$ mm hole.
- Simultaneous PIV & PLIF.
- Experimental (air, He only).
- $Ma = 0.4$ to 1.2.
- $Re = 16,000$ to 42,000.
- Momentum flux (force) matched [Panchapakesan and Lumley, 1993].

Figure: Jet configuration.
Introduction

Experimental Facility

Figure: Experimental Layout.
Results - Instantaneous velocity & concentration contours

Figure: Instantaneous a) velocity and b) concentration fields obtained from Helium 3D jet in XZ plane.
Results - Time-averaged velocity contours

Figure: Average velocity contours in $XZ$ and $YZ$ planes for 1) air and 2) helium, obtained from a) Round jet on side of tube (3D jet) and b) Round orifice plate (OP) jet.
Results - Time-averaged concentration contours

Figure: Average concentration contours in $XZ$ and $YZ$ planes for 1) air and 2) helium, obtained from a) 3D Round jet and b) Round orifice plate jet.
Results - Jet centerline

Figure: Jet centerlines taken along the location of maximum velocity ($|V|_{\text{max}}$) locations.
Results - Jet centerline properties

Figure: a) Jet inverse velocity decay and b) jet widths \(2(L/2)\) obtained along the \(|V|_c\) centerlines.
Results - Jet centerline properties (air)

Figure: Average velocity profiles, along jet centerlines, taken at various heights for air, obtained from a) OP & 3D jet in $XZ$ plane and b) 3D jet in $YZ$ planes.
Results - Jet centerline properties (helium)

Figure: Average velocity profiles, along jet centerlines, taken at various heights for helium, obtained from a) OP & 3D jet in $XZ$ plane and b) 3D jet in $YZ$ planes.
Figure : Average concentration profiles, along jet centerlines, taken at various heights for a) air and b) helium, obtained from OP & 3D jet in $XZ$ plane.
Conclusions

- Initial flow condition causes the jet to deflect from vertical axis.

- Realistic (3D) jets experience more jet spreading compared to the axisymmetric (round) jet experiments.
  - More jet spreading observed on back side of the asymmetric 3D jet compared to round jet.

- Enhanced mixing in the asymmetric case caused:
  - reduction in potential-core length
  - increase in the velocity decay rate.

- Conventional round jet assumptions are inadequate to predict near field:
  - gas concentration and velocity fields
  - entrainment rates
  - extents of the flammability envelope (i.e. for H2)
Acknowledgement

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### Table: Flow properties

<table>
<thead>
<tr>
<th>Jet</th>
<th>$Q$ [L/min($N_2$)]</th>
<th>$\bar{u}_{j(max)}$ [m/s]</th>
<th>$\rho_j$ [Kg/m$^3$]</th>
<th>$\nu$ [m$^2$/s]</th>
<th>$(\rho_j u_j)$ flux [N]</th>
<th>$Re$</th>
<th>$Fr$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D Air</td>
<td>15</td>
<td>147.5</td>
<td>1.17</td>
<td>$1.59 \times 10^{-5}$</td>
<td>0.1018</td>
<td>18554</td>
<td>N/A</td>
</tr>
<tr>
<td>OP Air</td>
<td>15</td>
<td>127.6</td>
<td>1.17</td>
<td>$1.59 \times 10^{-5}$</td>
<td>0.0762</td>
<td>16050</td>
<td>N/A</td>
</tr>
<tr>
<td>3D He</td>
<td>35</td>
<td>399.7</td>
<td>0.164</td>
<td>$1.91 \times 10^{-5}$</td>
<td>0.1048</td>
<td>41853</td>
<td>1144</td>
</tr>
<tr>
<td>OP He</td>
<td>35</td>
<td>341.9</td>
<td>0.164</td>
<td>$1.91 \times 10^{-5}$</td>
<td>0.0767</td>
<td>35801</td>
<td>978</td>
</tr>
</tbody>
</table>
Figure: Schematics of 3D jet and it’s Round 2mm slot geometry. All dimensions are in mm.
Appendix-3

Sharp-edged orifice (OP) jet

Figure: Schematic of the sharp-edged orifice jet apparatus, OP jet, (dimension in mm).
Appendix-4

Acetone a tracer for Gaseous Planar Laser-Induced Fluorescence (PLIF)

Why Acetone?

- High vapour pressure at room temperature absorbs over a wide band of wavelengths (225-320 nm) and emits fluorescence on even wider broadband of wavelengths (350-550 nm).
- Short fluorescence lifetime (∼ 2 ns).
- Low toxicity.
- Negligible oxygen quenching on fluorescence signal.
- It’s fluorescence signal in isothermal, isobaric flows is known to be linear with laser power and concentration.

![Acetone molecule](image)

Figure: Acetone (Dimethyl ketone, or 2-Propanone)
Appendix-5

Acetone PLIF

Fluorescence signal from Acetone PLIF in weak excitation (not saturated):

\[ S_f = n_{\text{tracer}}(T, p) \ dV_c \left[ \frac{E}{hc/\lambda} \right] \sigma(\lambda, T) \phi(\lambda, T, p, n_i) \eta_{\text{optic}} \] (1)

where;

- \( n_{\text{tracer}} \) is the number density of the tracer.
- \( dV_c \) is the collection volume.
- \( E \) is the laser energy fluence.
- \( hc/\lambda \) is the energy per photon of the laser at wavelength \( \lambda \).
- \( \sigma \) is the absorption cross-section of tracer molecule.
- \( \phi \) is the fluorescence yield.
- \( \eta_{\text{optic}} \) is the collection optics efficiency.
- \( T, p \) are temperature and pressure of the tracer, respectively.