A comparative study of plane and radial turbulent wall jets

Speaker: William Lin
Advisor: Prof. Eric Savory
Affiliation: Advanced Fluid Mechanics Research Group
www.eng.uwo.ca/research/afm

Sponsors:
Outline

1. Introductory remarks
   - Overview of two configurations
   - Motivation
   - Objectives
2. Plane wall jet velocity measurements
3. Comparison of plane and radial wall jets
4. Closing remarks
Brief overview of the plane wall jet

- Open slot top
- Open exit
- Outer layer
- Inner layer

Y
Brief overview of the radial wall jet

Diagram showing:
- Axis of symmetry
- Nozzle 1/2D
- Impingement regime
- Wall jet regime
- Open exit

Variables:
- $y_D$
- $y$
- $r$
Motivation

Applications:
• heating/cooling or drying/wetting
• removal or deposition of particles/films
• protective fluid layer
• modelling of storm outflows
Objectives

- To take velocity measurements of the plane turbulent wall jet
- To compare available experimental results from plane and radial wall jets.
Co-ordinate system
Nomenclature

\[ U_{m/2} \]

\[ y_{0.5} \]

\[ y_m \]

\[ U_m \]

\[ U_j \]

\[ t \]

\[ b \]
Experimental set-up

wire mesh

t/b = 1/9

Y/b = 19

x/b = 50 to 208
Experimental set-up

**Wire mesh**
- 16 x 16 openings/in²
- $D_{\text{wire}} = 0.46$ mm
- open area = 50.7%
Measurement apparatus

Dantec MiniCTA 54T30 system
- sampling frequency = 1 kHz

55P61 x-wire probe
- wire diameter = 5 x 10^{-6} m
- wire length = 1.25 x 10^{-3} m

Calibration
- Pitot-static tube + U-tube manometer

Traverse
- accuracy = 0.2 x 10^{-3} m

NI PCI-6071E card
- 12-bit resolution
Uncertainty analysis

Propagation-of-uncertainties approach
(Wheeler & Ganji 1996)

\[ \Delta U = \left[ \left( \frac{\partial U}{\partial A} \Delta A \right)^2 + \left( \frac{\partial U}{\partial B} \Delta B \right)^2 + \left( \frac{\partial U}{\partial C} \Delta C \right)^2 + \ldots \right]^{1/2} \]
Uncertainty analysis

Sources of uncertainty considered:

- Random variation of the measurand
- Ambient temperature variations during measurements
- Potential x-wire probe misalignment ($\leq 2^\circ$)
- Potential pitot-static tube misalignment ($\leq 2^\circ$)
- A/D conversion uncertainties
- Scale readability limitation of the calibration manometer
- Calibration curve-fitting
- X-wire probe yaw coefficient uncertainties
Uncertainty analysis

<table>
<thead>
<tr>
<th>U [m/s]</th>
<th>±ΔU [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>41</td>
<td>3.2</td>
</tr>
<tr>
<td>37</td>
<td>3.3</td>
</tr>
<tr>
<td>31</td>
<td>3.4</td>
</tr>
<tr>
<td>28</td>
<td>3.5</td>
</tr>
<tr>
<td>24</td>
<td>3.7</td>
</tr>
<tr>
<td>20</td>
<td>4.1</td>
</tr>
<tr>
<td>15</td>
<td>4.3</td>
</tr>
<tr>
<td>12</td>
<td>4.8</td>
</tr>
<tr>
<td>7.9</td>
<td>6.1</td>
</tr>
<tr>
<td>5.0</td>
<td>8.4</td>
</tr>
</tbody>
</table>
Plane wall jet velocity profiles

Study | $Re_b$ | $x/b$ | $t/b$ | $Y/b$ | similarity?
--- | --- | --- | --- | --- | ---
Present study | 4.0E+04 | 50, 150 | 0.1 | 21 | no
Wygnanski et al. (1992) | 1.9E+04 | 60 to 120 | <1 | 61 | no
Plane wall jet velocity profiles

$u = \frac{u_{RMS}}{U_m}$

$x/b = 50$

$x/b = 150$

Wygnanski et al. (1992)

Abrahamsson et al. (1994)

Present study
## Plane wall jet velocity profiles

<table>
<thead>
<tr>
<th>Study</th>
<th>Re&lt;sub&gt;b&lt;/sub&gt;</th>
<th>x/b</th>
<th>t/b</th>
<th>Y/b</th>
<th>similarity?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present study</td>
<td>4.0E+04</td>
<td>50, 150</td>
<td>0.1</td>
<td>21</td>
<td>no</td>
</tr>
<tr>
<td>Wygnanski et al. (1992)</td>
<td>1.9E+04</td>
<td>60 to 120</td>
<td>&lt;1</td>
<td>61</td>
<td>no</td>
</tr>
<tr>
<td>Eriksson et al. (1998)</td>
<td>9.6E+03</td>
<td>40 to 150</td>
<td>107</td>
<td>108</td>
<td>yes</td>
</tr>
<tr>
<td>Abrahamsson et al. (1994)</td>
<td>1.0E+04, 2.0E+04</td>
<td>70 to 150, 125 to 150</td>
<td>239</td>
<td>240</td>
<td>yes</td>
</tr>
</tbody>
</table>
Jet spread

\[ \frac{y_{0.5}}{b} = A \left( \frac{x + x_0}{b} \right)^m \]

\( m = 1 \)

(14 of 16 experiments)
Velocity profile comparison

- **Plane Wall Jet**
  - $x/b = 50$
  - $Re_b = 4E4$
  - Verhoff (1970)
  - $Re_b \approx 1E4$

- **Radial Wall Jet**
  - $r/D \geq 1.5$, $Re_D = 4E5$, $y_n/D = 2$
  - Knowles & Myszko (1998)
  - $r/D \geq 2.0$, $Re_D = 9E4$, $y_n/D = 10$
  - Wood et al. (2001)
  - $Re_b = 1E4$
Velocity profile comparison

**Plane wall jet** (Verhoff 1970)

\[ \frac{U}{U_m} = 1.48 \left( \frac{y}{y_{0.5}} \right)^{1/7} \left( 1 - \text{erf} \left( 0.68 \left( \frac{y}{y_{0.5}} \right) \right) \right) \]

**Radial wall jet** (Wood et al. 2001)

\[ \frac{U}{U_m} = 1.55 \left( \frac{y}{y_{0.5}} \right)^{1/6} \left( 1 - \text{erf} \left( 0.70 \left( \frac{y}{y_{0.5}} \right) \right) \right) \]
Velocity profile comparison

\[ I_u = \frac{u_{RMS}}{U_m} \]

- Present study
- Abrahamsen et al. (1994)
- Knowles & Myszko (1998)

Conditions:
- radial wall jet
- plane wall jet
- \( r/D = 2.0, \ Re_D = 9 \times 10^4, y_D/D = 10 \)
### Jet spread comparison

#### Plane wall jet

<table>
<thead>
<tr>
<th>Authors</th>
<th>Data range x/b</th>
<th>Re&lt;sub&gt;b&lt;/sub&gt;</th>
<th>Jet spread m</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bradshaw &amp; Gee [18]</td>
<td>339 to 1459</td>
<td>6.0E+03</td>
<td>1</td>
<td>0.071</td>
</tr>
<tr>
<td>Eriksson et al. [22]</td>
<td>5.2 to 208</td>
<td>9.6E+03</td>
<td>1</td>
<td>0.078</td>
</tr>
<tr>
<td>Wygnanski et al. [20]</td>
<td>30 to 100</td>
<td>1.0E+04</td>
<td>0.88</td>
<td>??</td>
</tr>
<tr>
<td>Abrahamsson et al. [13]</td>
<td>30 to 175</td>
<td>1.0E+04</td>
<td>1</td>
<td>0.081</td>
</tr>
<tr>
<td>Verhoff [15]</td>
<td>104 to 417</td>
<td>1.0E+04</td>
<td>1</td>
<td>0.082</td>
</tr>
<tr>
<td>Schwarz &amp; Cosart [14]</td>
<td>24 to 42</td>
<td>1.4E+04</td>
<td>1</td>
<td>0.085</td>
</tr>
<tr>
<td>Schneider &amp; Goldstein [23]</td>
<td>43 to 110</td>
<td>1.4E+04</td>
<td>1</td>
<td>0.077</td>
</tr>
<tr>
<td>Abrahamsson et al. [13]</td>
<td>30 to 175</td>
<td>1.5E+04</td>
<td>1</td>
<td>0.077</td>
</tr>
<tr>
<td>Wygnanski et al. [20]</td>
<td>30 to 140</td>
<td>1.9E+04</td>
<td>0.88</td>
<td>??</td>
</tr>
<tr>
<td>Abrahamsson et al. [13]</td>
<td>70 to 175</td>
<td>2.0E+04</td>
<td>1</td>
<td>0.075</td>
</tr>
<tr>
<td>Schwarz &amp; Cosart [14]</td>
<td>24 to 42</td>
<td>2.0E+04</td>
<td>1</td>
<td>0.069</td>
</tr>
<tr>
<td>Gartshore &amp; Hawaleshka [16]</td>
<td>18 to 124</td>
<td>3.1E+04</td>
<td>1</td>
<td>0.066</td>
</tr>
<tr>
<td>Schwarz &amp; Cosart [14]</td>
<td>24 to 42</td>
<td>4.2E+04</td>
<td>1</td>
<td>0.061</td>
</tr>
<tr>
<td>Förthmann [12]</td>
<td>3 to 33</td>
<td>5.4E+04</td>
<td>1</td>
<td>0.082</td>
</tr>
</tbody>
</table>

**Arithmetic mean:** 0.074  
**Sample standard deviation:** 0.008

#### Radial wall jet

<table>
<thead>
<tr>
<th>Authors</th>
<th>Data range r/D</th>
<th>Re&lt;sub&gt;D&lt;/sub&gt;</th>
<th>y&lt;sub&gt;D&lt;/sub&gt;/D</th>
<th>Jet spread n</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bakke [4]</td>
<td>5 to 10.7</td>
<td>6.4E4</td>
<td>0.53</td>
<td>0.94</td>
<td>??</td>
</tr>
<tr>
<td>Cooper et al. [7]</td>
<td>3 to 7</td>
<td>2.3E4</td>
<td>2</td>
<td>1</td>
<td>0.073</td>
</tr>
<tr>
<td>Knowles &amp; Myszko [8]</td>
<td>2 to 9</td>
<td>9.0E4</td>
<td>2</td>
<td>1</td>
<td>0.091</td>
</tr>
<tr>
<td>Bradshaw &amp; Love [5]</td>
<td>3.2 to 20</td>
<td>1.8E5</td>
<td>18</td>
<td>1</td>
<td>0.088</td>
</tr>
</tbody>
</table>

**Arithmetic mean:** 0.089  
**Sample standard deviation:** 0.013
Conclusions

- Turbulence profile similarity dependency on slot top geometry
- Profiles of time-averaged velocity for plane and radial wall jets match within experimental error
- Linear spread rate of plane wall jet
  
  \[ = 0.83 \text{ linear spread rate of radial wall jet} \]
Future work

• turbulence profile similarity dependency on slot top geometry

• investigation of the Re_b dependency of the velocity decay parameters

• measurements in large plane wall jet facility (2.5 m x 2 m cross-section)
Acknowledgements

Sponsors:

• UWO University Machine Shop
• C. Novacco
• Dr. G.A. Kopp and Dr. R.J. Martinuzzi

Advanced Fluid Mechanics Research Group
www.eng.uwo.ca/research/afm