# Project Themis: Water Visualization Study

## 4. TITLE AND SUBTITLE

Project Themis: Water Visualization Study

## 5. AUTHOR(S)

Allen Bishop

## 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/RZSE
4 Draco Drive
Edwards Air Force Base CA 93524-7160

## 8. PERFORMING ORGANIZATION REPORT NUMBER

AFRL/RZSE

## 9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/RZS
5 Pollux Drive
Edwards AFB CA 93524-7048

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Thesis Presentation, Cal Poly University, San Luis Obispo, CA, December 2011.

## 14. ABSTRACT

This presentation examines the background of transverse jets and their problems, parameters and design space. Apparatus is discussed, including water flow loop and test section parts, as well as flow measurements, LDV, PLIF, and results, Holdeman Scaling and unmixedness.

## 15. SUBJECT TERMS

[Identification of specific subject terms, if available]

## 16. SECURITY CLASSIFICATION OF:

<table>
<thead>
<tr>
<th>a. REPORT</th>
<th>b. ABSTRACT</th>
<th>c. THIS PAGE</th>
</tr>
</thead>
<tbody>
<tr>
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</tbody>
</table>

## 17. LIMITATION OF ABSTRACT

SAR

## 18. NUMBER OF PAGES

61

## 19. NAME OF RESPONSIBLE PERSON

Mr. Nils M. Sedano

## 19b. TELEPHONE NUMBER (include area code)

N/A
Project Themis: Water Visualization Study

Allen Bishop
AFRL/RZSE
15 Sept 2011
About Me

- BS & MS Aerospace Engineering
  Cal Poly, San Luis Obispo

- Work Experience
  - AFFTC/812 TSS Eng. Outreach (June-Sept 2009)
  - AFRL Themis Co-Op (Apr 2010-Sept 2011)
  - Florida Turbine Technologies – Aero/Heat Xfer (Oct 2011 – future)

- Hobbies
  - Guitar
  - Mountain biking
  - Ballroom dancing
Outline

• Background
  • Transverse Jets
  • Problem Statement
  • Non-Dimensional Parameters
  • Design Space
• Apparatus
  • Water Flow Loop
  • Test Section Parts
• Flow Measurement
  • LDV
  • PLIF
• Results
  • Holdeman Scaling
  • Unmixedness
Introduction
Background

- Transverse jets (jets-in-crossflow) have been studied extensively in academia and industry
- Applications:
  - Smokestack dispersion
  - Gas turbine burners
  - VTOL Aircraft
- Use is well established in mixing of two dissimilar fluids for combustion devices
- Certain regimes of multiple jets have not been studied and are currently of interest to Air Force research goals
Problem Statement

- AF seeking to develop reusable high-performance liquid rocket engine
- Hindrances to reusability are turbine cycle fatigue and oxygen compatibility
- Turbine cycle fatigue issues
  - Density
  - Species
  - Temperature
Project Objective

- Investigate mixing behavior of multiple confined JICF to determine local optima
- Control parameters include velocity ratio, diameter ratio and number of jets
- Non-dimensional (ND) parameters of interest for scaling include momentum flux ratio, momentum ratio and others
Studies have historically focused on gas turbine applications involving rectangular ducts or free jets.

Holdeman et al. studied 8-12 cylindrical orifices in a confined can. Downstream profiles similar when scaled with orifice spacing \((S/D_c)\) and the square root of the momentum flux ratio.

For most cases, \(C \approx 2.5\) (empirical)

The optimum momentum flux ratio can then be given by:

\[
I_{opt} = \frac{1}{2} \left( \frac{C n_j}{\pi} \right)^2
\]

Momentum Flux Ratio: \(I = \left( \frac{\rho_j}{\rho_c} \right) \left( \frac{v_j}{v_c} \right)^2\)

\(S = \frac{\pi D_c}{n_j}\)
Gas turbine combustors commonly use temperature as a means of analogizing concentration since they are both scalar quantities. The non-dimensional temperature can be defined as:

$$\theta = \frac{T_m - T}{T_m - T_j}$$

Using optical techniques, concentration can instead be analogized by light intensity (non-intrusive).

Spatial unmixedness can then be defined from the variance and normalized:

$$U = \frac{1}{m} \sum_{i=1}^{m} (C_i - \bar{C})^2 \over \bar{C}^2$$

Where $m$ is the pixel count and $C$ is concentration determined from calibration data and field corrections.
Relevant Ratios

- **Density Ratio**
  \[ \pi_1 = \frac{\rho_j}{\rho_c} \]

- **Velocity Ratio**
  - Velocity of a single jet divided by crossflow
  \[ \pi_2 = \frac{v_j}{v_c} \]

- **Diameter Ratio**
  - Diameter of a single jet divided by crossflow
  \[ \pi_3 = \frac{d_j}{d_c} \]

- **Number of Jets**
  \[ \pi_4 = n_j \]

Not a priority in water flow experiment.
Methodology

- Fix jet mass flow rates by cavitating venturis
- Adjust velocity ratio by changing core mass flow rate/core velocity for given geometry
  \[ \pi_2 = \frac{v_j}{v_c} \]
- Fix core diameter via standard test section
- Adjust jet diameters via interchangable inserts
  \[ \pi_3 = \frac{d_j}{d_c} \]
- Maximum number of jets set by test section
- Use “blank” inserts to reduce the number of jets
  \[ \pi_4 = n_j \]
How to determine relative ranges of velocity ratio, diameter ratio, and number of jets?

- Holdeman et al studied numbers of jets from 8-16.
- Knowledge at lower n-values important for AF research goals.
- 2, 3, 6 decided upon for symmetric injection.
- Previous JICF work estimates diameter ratios between 0.1-0.3.
- Used knowledge of pre-existing water flow facility to approximately size core diameter and jet diameters.

Jets start to impede at $D_j/D_c = 0.833$. 

Main Flow
Design Space

- Previous JICF work studies J values from 5-200
- AF research focused on J ≈ 10-50
- Relevant velocity ratios set as square root of these values

- Previous JICF work estimates diameter ratios between 0.1-0.3
- Used knowledge of pre-existing water flow facility to approximately size core diameter and jet diameters
- Based on mass flow available, selected 0.12-0.21 as possible diameter ratios

Core Flow (2-20 GPM)
Jet Flow (0.71 GPM/jet)
Design Space

Facility Flow Rate Limit (~2.3 GPM)

Range of Investigation

Njets = 2

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Design Space

\[ \pi_2 = [\sqrt{10} \quad \sqrt{20} \quad \sqrt{30} \quad \sqrt{40} \quad \sqrt{50}] \]
\[ \pi_3 = [0.12 \quad 0.165 \quad 0.21] \]
\[ \pi_4 = [2 \quad 3 \quad 6] \]

- Changing diameter ratio or number of jets requires hardware change
- Changing number of jets is slightly easier, since certain inserts will be left in place and others will be blocked off by using “blanks”
- Diameter ratio/number of jets assigned fewer values to minimize hardware changeover while still covering parameters of interest
- Velocity ratio easiest to change, assigned more test points in order to increase strength of correlations
Apparatus
Water Flow Loop

- Pre-existing hardware, being remodeled to accommodate JICF
- Recirculating loop, tank open to atm., manually operated
- Approx. capabilities: 100 psi discharge, 100 gpm, inlet temp 10 – 40 °C
- Good control of fluid temp, pressure & flow rate
Water Flow Loop

- Water Tank
  - 60 gal cap
  - Open to atm
- Pump
  - Ebara A3U32-200
  - 10 hp (variable RPM)
  - Q @ 10-120 GPM
  - H @ 10-100 psi

Operating Curves for Ebara Pump Model A3U32-200-10hp

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Water Flow Loop

- Line sizes (D = 1” or 2”) allows low or high Q operation while controlling velocity
- Using 1” line for most tests
Modified Flow Loop

- Introduced injection piping
- Water used for shakedown/start-up
- Fluorescein used for data collection

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Turbulent Run-Up

- Orifice plate between inlet and turbulent run up to increase hydraulic resistance of the test section
- 1.5” PVC nominal
LDV Window

• Provides optical access before test section
• LDV crosshairs will traverse the window laterally to measure the inlet velocity profile (mean and turbulent fluctuations)
• Characterize for all potential core inflow velocities
Injection Block

- Focal point of jets
- Nylon, machined on-site by AFRL techs
- Injection cross section is same as turbulent run-up (1.5” nominal)
Jet Inserts

- All jet inserts machined the same for interchangability
- Characterize using LDV system
- Ajayi, Papadopoulos and Durst (1998) concluded that $x/D \approx 20$ sufficient for velocity normalization ($5300 < Re < 10000$)

<table>
<thead>
<tr>
<th>$D_j/D_c$</th>
<th>$L/D_j$</th>
<th>$Re_j$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.12</td>
<td>35.6</td>
<td>10430</td>
</tr>
<tr>
<td>0.165</td>
<td>25.9</td>
<td>7590</td>
</tr>
<tr>
<td>0.21</td>
<td>20.3</td>
<td>5960</td>
</tr>
</tbody>
</table>
Injection Manifold

- Pressure drop across injection manifold is minimal
- Variation between lines is < 0.07 psi
- Resulting $\Delta Q$ between lines is < 1%

From injection tanks

Cavitating venturis

Tees for pressure taps

Ball valves

To injectors
Measurement Window

- Laser Access
- Collection Plenum
- Measurement Plane
- Plexi Test Section
- Data Camera
Flow Measurement
miniLDV System

- Lenses, beam splitter, and photodetector housed in a single unit
- Powered by 60 mW diode laser (output power 44 mW)
- Measurement specs:
  - 1 mm/s – 300 m/s
  - Accuracy 99.7%
  - Delivers U and u’

Image Credit: Measurement Sciences
LDV Profiles

Q = 1.61 GPM

- LDV (Re = 3077)
- van Doorne PIV (Re = 5300)
- den Toonder LDV (Re = 4900)

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LDV Profiles

Q = 2.34 GPM

- LDV (Re = 4468)
- van Doorne PIV (Re = 5300)
- den Toonder LDV (Re = 4900)

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LDV Profiles

Q = 8.30 GPM

\( \text{den Toonder} \quad (Re=17800) \)

\( \text{LDV Raw} \quad (Re=15900) \)
Planar Laser Induced Fluorescence

- Laser spread to a sheet using a cylindrical lens
- Laser energy excites fluorescent agent seeded into fluid of interest
- Calibrate using:
  - Laser Sheet Intensity
  - Injection fluid concentration
  - Exposure time

Image Credit: R. McLaughlin, University of North Carolina, Chapel Hill
Planar Laser Induced Fluorescence

- Fluorescent agent is sodium fluorescein (C_{20}H_{10}Na_{2}O_{5})
- Benefits:
  - High quantum yield (~94%)
  - Water soluble
  - Relatively safe
- Other chemicals considered were Rhodamine (G and 6B); downselected for safety and ease of handling
- Absorption spectrum overlaps sufficiently with Ar-Ion laser @ 514 nm

<table>
<thead>
<tr>
<th>Absorption Max</th>
<th>~494 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission Max</td>
<td>~521 nm</td>
</tr>
</tbody>
</table>

Image Credit: Invitrogen
In-Situ Calibration

- Raw field intensity
  - Data set taken per test
  - 3-4 images per test
- Dark field intensity
  - Taken before each test
  - Background correction for camera pixels
- Reference field intensity
  - Taken daily
  - Fluid-filled test section at pure jet fluid concentration
  - Accounts for attenuation, beam shape and other environmental factors

\[
I_{NORM} = \frac{I_{RAW} - I_{DF}}{I_{REF} - I_{DF}}
\]

Sample reference image
Highpass Filtered at 530 nm
C = 4.8x10^{-8} \text{ mol/L}
f-stop = 11
Exp time = 2 sec

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Results

We’re not kidding!
Proposed Results

- **Holdeman deviation**
  - \( n_j < n_{\text{critical}} \) (\( \approx 6 \))
  - \( J_{\text{opt}} = \frac{1}{2} \left( \frac{C n_j}{\pi} \right)^2 \)

- **Show how unmixedness varies with ND parameters**

- **Concentration images**

- **Analysis of macro-level spatial flow features**
Unmixedness

N = 1

N = 2

N = 3

N = 6

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Unmixedness

Mixing vs J

Unmixedness

Momentum Flux

N = 1
N = 2
N = 3
N = 6

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Sample Case – N6_J30_D12

Processed image with contours

Raw image

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Holdeman Plot

Mixing vs J

Optimum Momentum Flux

Number of Jets

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Conclusions

• Sparse multi-JICF behave much how we expect

• Break-off point with Holdeman scaling slightly higher than theory predicts (2π ~ 6.28)

• Diminishing returns moving from 3 to 6 jets

• Take-away: there is an optimum J-value for the six-jet configuration near J = 30
Future Work

• Obtain remainder of data for higher diameter ratios*
• Look at other axial locations for promising cases*
• Re-evaluate data anomalies
• Write a thesis? (no big deal)

*Themis work
Lessons Learned (Gripes)

• Government work is just as slow as everyone jokes

• Experimentation is full of headaches
  – Tight fitting of jet inserts with injection block
  – Determining appropriate concentration
  – Rusty tanks
  – Old pressure transducers
  – Leaks, leaks, leaks
  – Having to explain to safety that fluorescein is less dangerous than vacuum pockets
  – Fixing Labview (and logistics of dealing with IT)
  – Doing it all on a shoestring budget

• Just use gases, they’re way more simple
Project Themis: Water Visualization Study

Cal Poly
Dr. Tina Jameson (chair)
Dr. Dianne DeTurris
Dr. David Marshall

AFRL
Dr. Rich Cohn
Nils Sedano
Dr. David Forliti

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Back-Ups
Transverse Jets

Unconfined single transverse jets (single phase)
- Exhaust stacks, V/STOL aircraft, 3D canonical flow
- Studied extensively in literature
  - Fric and Roshko (1994) cited 358 times
  - Smith and Mungal (1998) cited 201 times
  - Yuan, Street and Ferziger (1999) cited 155 times
  - Margason review article (1993) cited 165 times
- Multiple vortex structures
- Scaling laws

Unconfined single transverse jets (two phase)
- Atomization of liquid jets
- Supersonic gas-phase velocities (Scramjet application)

Confined multiple transverse jets
- Motivated to support gas turbine combustor design
- Holdeman (NASA Glenn) and coworkers major contributor
Transverse Jet Anatomy

- Counter-rotating Vortex Pair (CVP)
- Horseshoe vortex forms at forward stagnation point
- Wake vortices shed from jet
- Occur over a wide range of Reynolds numbers

Image Credit: Fric and Roshko (1994)
Current US Launch Systems

Delta IV (Boeing/ULA)
- First Stage: 1 RS-68
- Propellants: LOX/LH2

Atlas V (Lockheed Martin/ULA)
- First Stage: 1 RD-180
- Propellants: LOX/RP-1
Parameters and Scaling Laws

Physical argument for the Holdeman parameter

For good mixing, jet penetration $\sim$ Radius

$$l_c^2 U_c^2 = D_j^2 U_j^2$$

$$l_c^2 \propto R_c D_j \sim \text{blockage}$$

Jet length scale is $rD_j$:
• Jet strongly deflected in a streamwise length of $rD_j$
• Jet growth to a width of $\sim rD_j$

Good mixing:
Jets far enough apart to allow CVP to form
Jets close enough to begin to merge when they approach a size of $rD_j$

$$D_j r \propto S$$
$$D_j r^2 \propto R_c$$

$$S r \propto R_c$$

argue $r \propto J^{1/2}$

$$C = \frac{S}{R_c} \sqrt{J}$$
ND Groups

- Used Buckingham-Pi to determine relevant dimensionless parameters

- Relevant equations:

<table>
<thead>
<tr>
<th>Continuity</th>
<th>Momentum</th>
<th>Total Momentum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{m}_j = \rho_j A_j v_j$</td>
<td>$\rho_j A_j v_j^2$</td>
<td>$\rho_j A_j v_j^2 n_j$</td>
</tr>
<tr>
<td>$\dot{m}_c = \rho_c A_c v_c$</td>
<td>$\rho_c A_c v_c^2$</td>
<td>$\rho_c A_c v_c^2$</td>
</tr>
</tbody>
</table>

- Recurring Variables:

$\rho_j \rho_c v_j v_c d_j d_c n_j$

- Other Variables

$\mu_j \mu_c$
# Parameters of Interest

<table>
<thead>
<tr>
<th>ND Parameter</th>
<th>Equations</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum Flux Ratio</td>
<td>[ J = \left( \frac{\rho_j}{\rho_c} \right) \left( \frac{v_j}{v_c} \right)^2 ]</td>
<td>Prominent in literature</td>
</tr>
<tr>
<td>“Kappa”</td>
<td>[ \kappa = \sqrt{\left( \frac{\rho_j}{\rho_c} \right) \left( \frac{v_j}{v_c} \right)^2 \left( \frac{d_j}{d_c} \right)} ]</td>
<td>Proportional to rD scaling</td>
</tr>
<tr>
<td>“Lambda”</td>
<td>[ \lambda = \sqrt{\left( \frac{\rho_j}{\rho_c} \right) \left( \frac{v_j}{v_c} \right)^2 \left( \frac{d_j}{d_c} \right) n_j} ]</td>
<td>Proportional to rD scaling</td>
</tr>
<tr>
<td>“Alpha”</td>
<td>[ \alpha = \left( \frac{\rho_j}{\rho_c} \right) \left( \frac{v_j}{v_c} \right)^2 \left( \frac{d_j}{d_c} \right) ]</td>
<td>Proportional to r^2D scaling</td>
</tr>
<tr>
<td>“Epsilon”</td>
<td>[ \varepsilon = \left( \frac{\rho_j}{\rho_c} \right) \left( \frac{v_j}{v_c} \right)^2 \left( \frac{d_j}{d_c} \right) n_j ]</td>
<td>Proportional to r^2D scaling</td>
</tr>
<tr>
<td>Momentum Ratio</td>
<td>[ \beta = \left( \frac{\rho_j}{\rho_c} \right) \left( \frac{v_j}{v_c} \right)^2 \left( \frac{d_j}{d_c} \right)^2 ]</td>
<td>Prominent for certain jet types</td>
</tr>
<tr>
<td>Total Momentum Ratio</td>
<td>[ \psi = \left( \frac{\rho_j}{\rho_c} \right) \left( \frac{v_j}{v_c} \right)^2 \left( \frac{d_j}{d_c} \right)^2 n_j ]</td>
<td>Accounts for jet interaction</td>
</tr>
</tbody>
</table>
Laser Doppler Velocimetry (LDV)

- Use interference patterns and Mie scattering to calculate bulk flow velocity.
- Using geometry, the fringe spacing $\delta$ can be determined from laser wavelength and convergence angle $\theta$:

$$\delta = \frac{\lambda}{2 \sin \left( \frac{\theta}{2} \right)}$$

- Whenever a scattering particle crosses one of these interference planes, it will be sensed by a photodetector.

Image Credit: eFunda
Laser Doppler Velocimetry

• Particles will periodically pass through interference planes (not continuously)
• This corresponds to the Doppler burst frequency: \[ f_D = \frac{v_N}{\delta} \] where \( v_N \) represents the component of velocity normal to the interference plane

• Limitations:
  • Cannot predict direction
  • True velocity must be estimated by normal component

• Advantages:
  • Relatively simple
  • Non-intrusive

Image Credit: eFunda

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LDV Profiles

Q = 1.61 GPM

LDV (Re = 3000)

van Doorne

Distribution A. Approved for public release; distribution unlimited
LDV Profiles

Q = 2.34 GPM

LDV (Re = 3800)  
van Doorne

Distribution A. Approved for public release; distribution unlimited
LDV Profiles

Q = 8.30 GPM

den Toonder
(Re=17800)

LDV Raw
(Re=15900)

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Sample PLIF Setup

- Laser (Ar-Ion)
- Redirection Mirrors
- Test Article
- Yellow Filter (~530 nm)
- CCD Camera

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General PLIF Considerations

- Fluid pH > 9
- Photobleaching
- Fluid purity
- Laser power
- Beam/sheet attenuation
- Camera
- Environment and background correction

Shadow streaking as a result of fluid impurities

Laser Attenuation vs. Distance

- 100 mW
- 150 mW
- 200 mW
- 250 mW
- 300 mW
- 350 mW
- 400 mW
- 450 mW