Proper orthogonal decomposition based feature identification on a round jet in cross-flow

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* - presenting

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Motivation

- **Weak volcanic plumes**
  - Volcanic ash ejection
  - Safety and visibility hazard/warnings
  - Eyjafjallajökull eruption, Iceland, 2010
- Plumes in cross-wind ➔ **round jet in cross-flow**
- Turbulence studies in a closed-circuit wind tunnel
  - **Varying inflow velocity**
  - Varying turbulence intensity
  - Varying gas density

Turbulent Flow

instantaneous velocity at given point in given snapshot

mean velocity at given point over all snapshots

fluctuation from the mean at given point in given snapshot

$$U = \overline{U} + u'$$

Instantaneous Snapshots

Mean Flow Statistics

$\overline{U}$ $\overline{V}$ $\overline{W}$

Reynolds stresses

$\overline{u'u'}$ $\overline{v'v'}$ $\overline{u'v'}$

Proper Orthogonal Decomposition (POD)

- **Statistical tool,** analyzes instantaneous velocity snapshots
- Matrix operations extract **dominant features** of system
- Modes identified, ordered **from highest to lowest energy**
- Flow fields **reconstructed** using preferred modes

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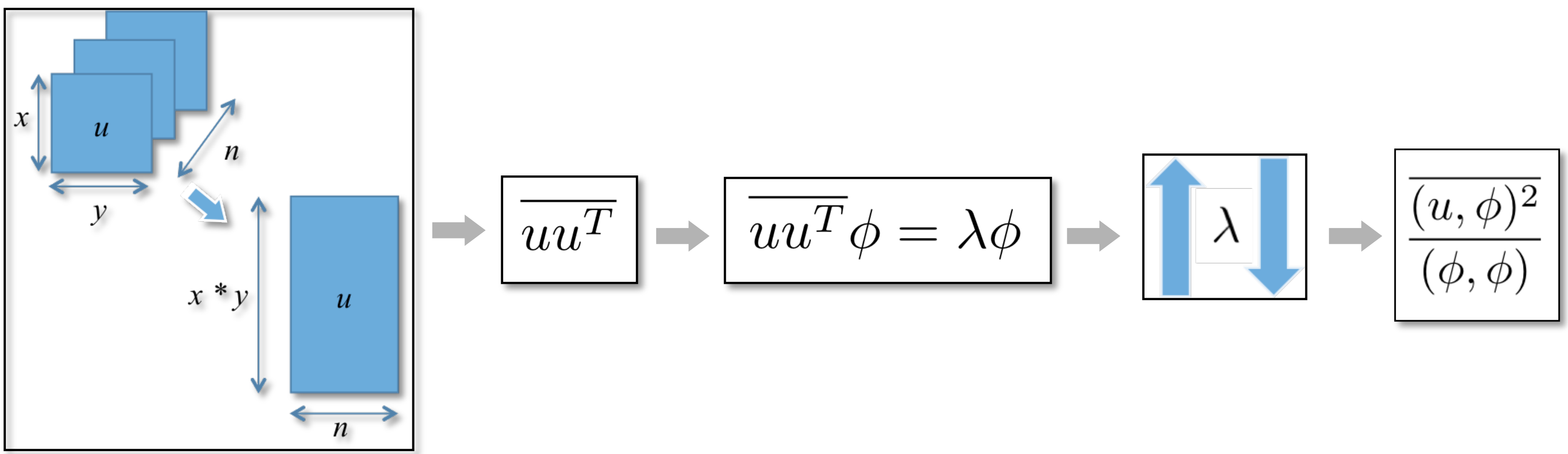
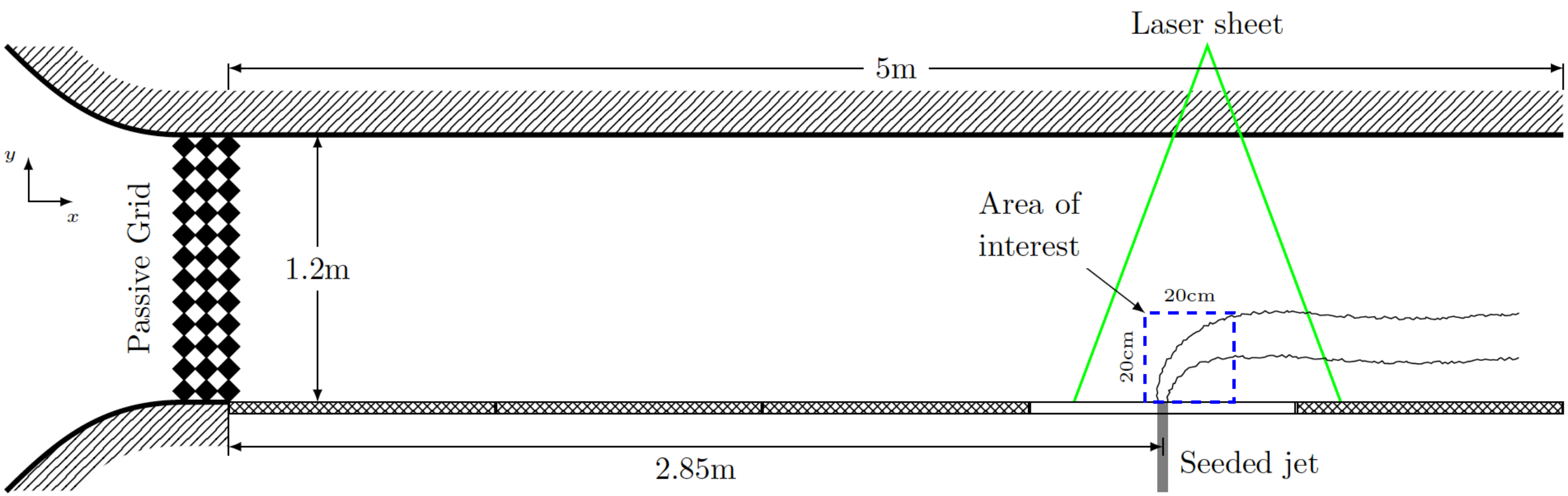


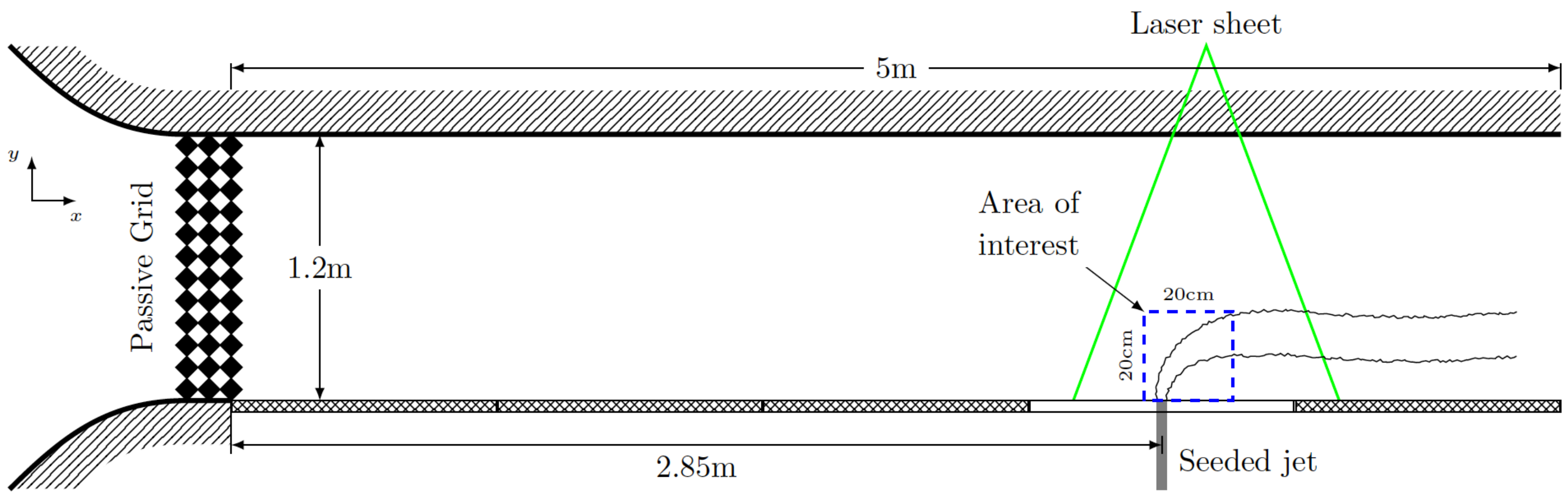
Experimental Setup



Wind Tunnel

- Portland State University's closed-circuit wind tunnel
- Test section: 5m length, 0.8m x 1.2m cross-section
- Area of interest: 0.2. x 0.2m
- Turbulence grid: Passive state
- Round jet: particle-seeded, perpendicular to flow, 9.525mm diameter

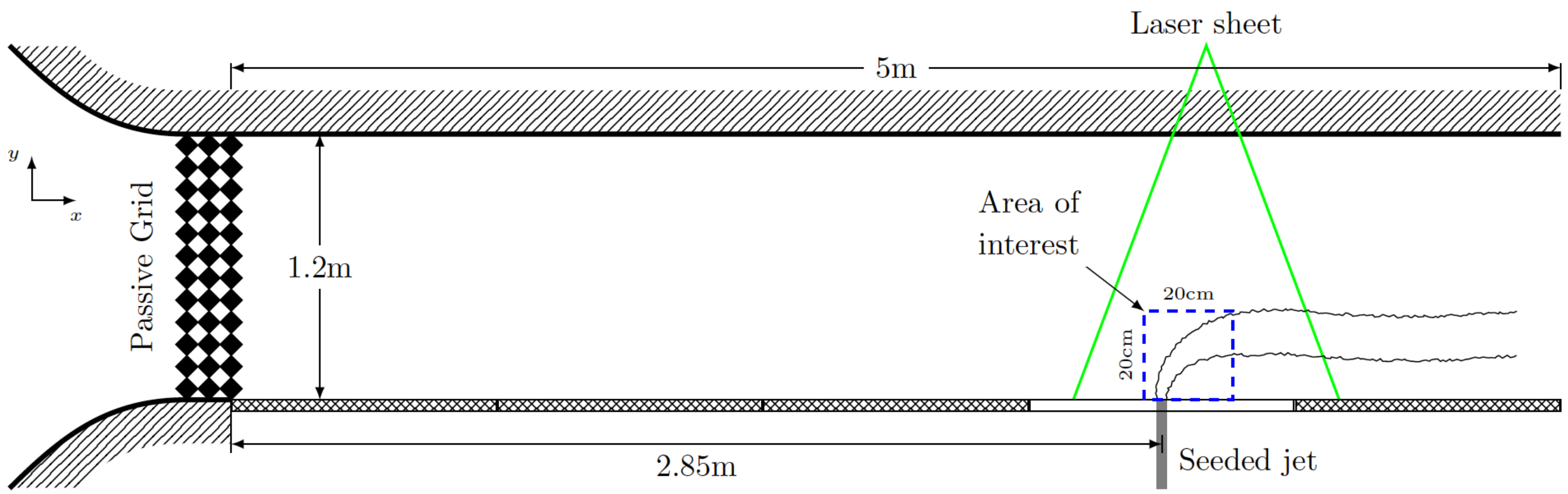
Experimental Setup



Particle Image Velocimetry (PIV)

- PIV system: LaVision™,
- PIV software DaVis™
- Two 4MP ImagerProX CCD cameras
- Non-time-resolved, stereoscopic images
- ~2500 snapshots per case, two cases considered

Experimental Setup



inflow velocity

jet velocity

v_∞ (m/s)	v_{jet} (m/s)	R_v
1.87	26.01	13.90
2.68	26.01	9.70

$R_v = v_{jet}/v_\infty$

Mean Flow Statistics

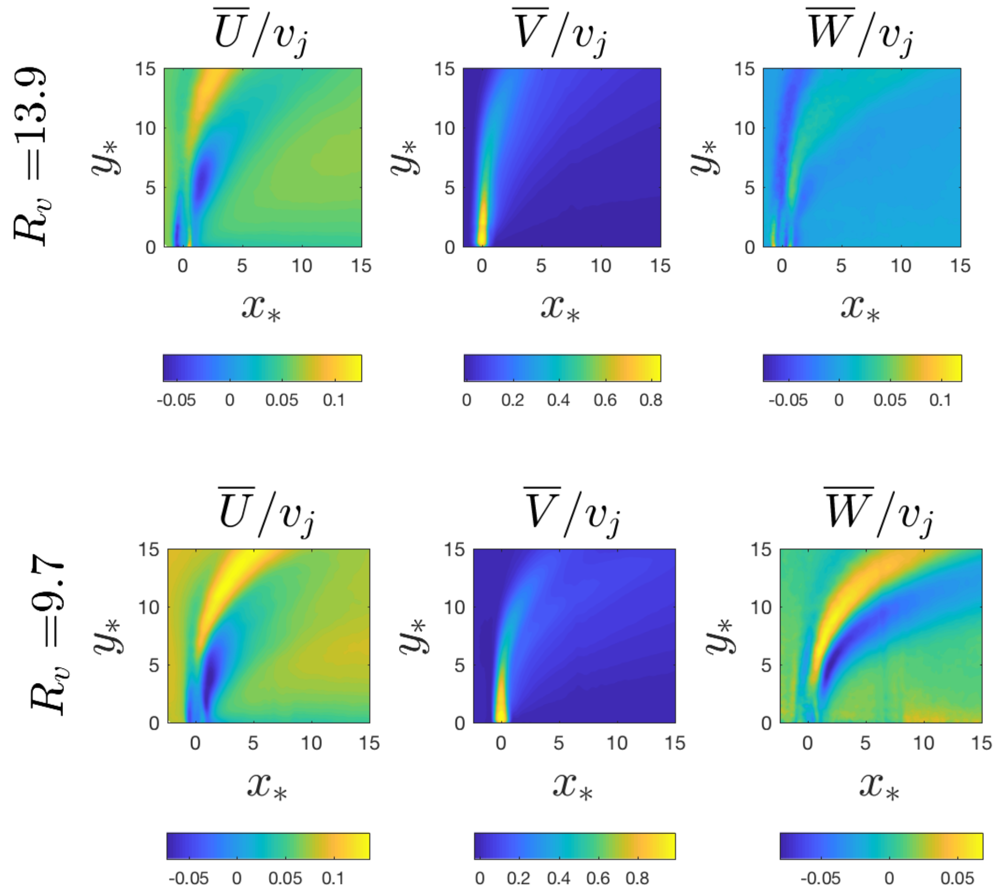


Figure 1. Mean flow statistics of instantaneous velocity for R_v=*13.9* (top) and R_v=*9.7* (bottom). *U* is the mean velocity of the fluid in the stream-wise direction, *V* the mean velocity in the vertical direction, and *W* the velocity in the out-of-plane.

Reynolds Stresses

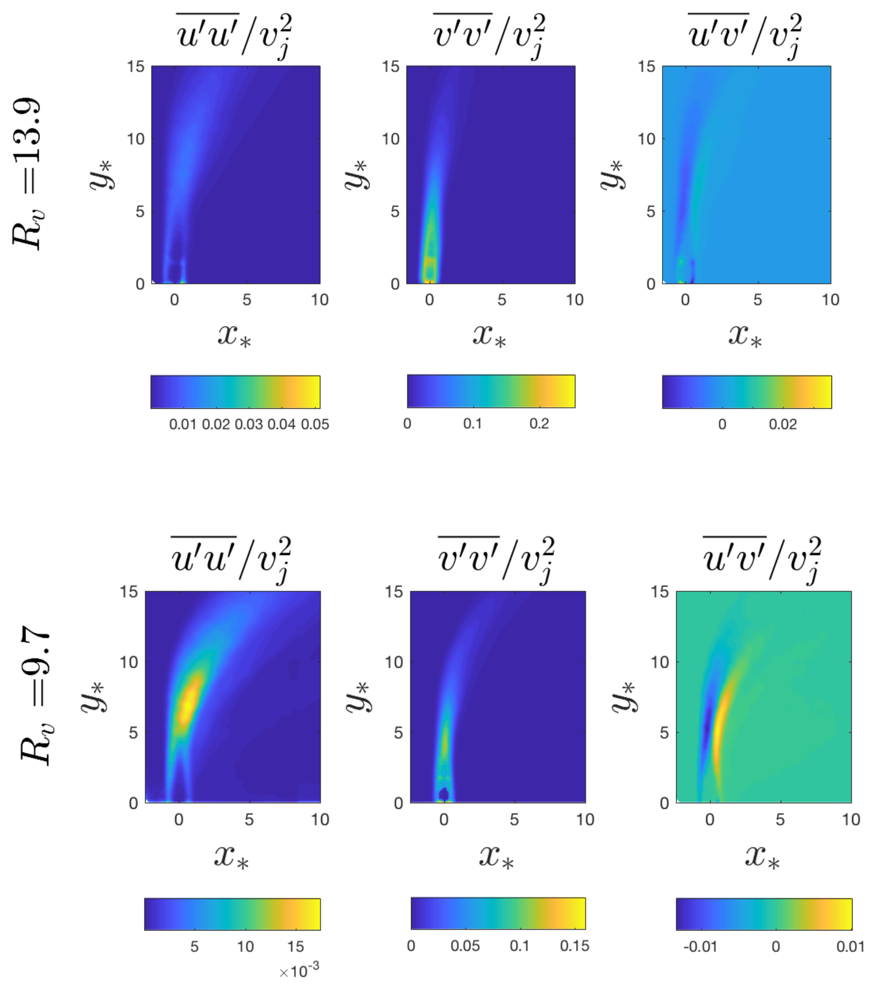
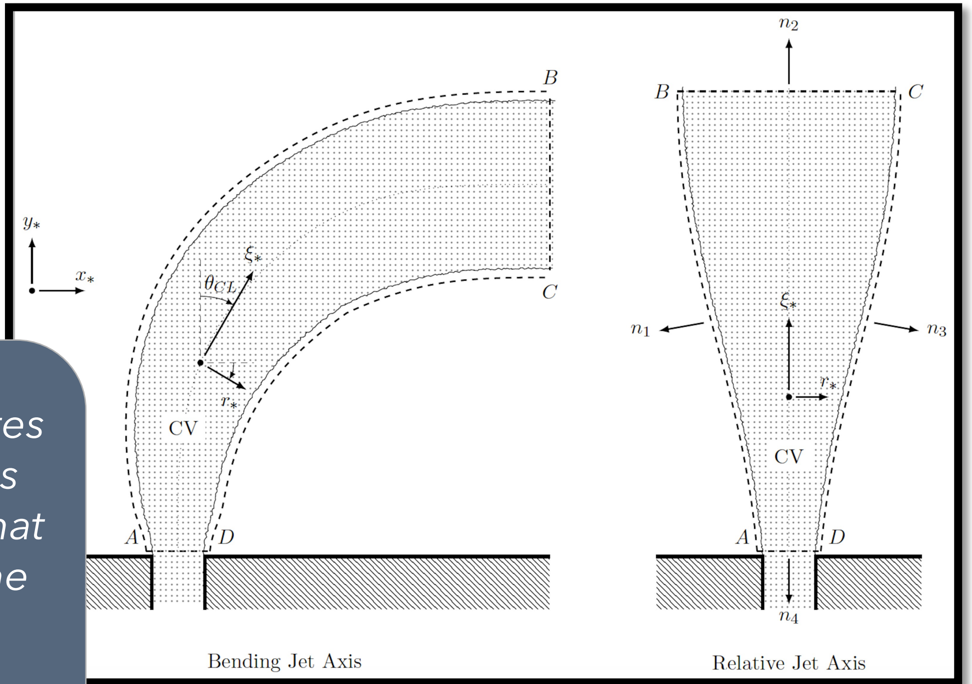


Figure 2. Reynolds stresses , *u'u'*, *v'v'*, and *u'v'* for R_v=*13.9* (top) and R_v=*9.7* (bottom). Stresses *u'u'* and *v'v'* are the normal components of interest, and *u'v'* is the shear-component stress.

Change of Axes



Cartesian coordinates and velocity data is transformed such that the centerline of the jet is a straight, vertical line

$$\begin{bmatrix} r_* \\ \xi_* \\ z_* \end{bmatrix} = \begin{bmatrix} \cos\theta_{CL} & -\sin\theta_{CL} & 0 \\ \sin\theta_{CL} & \cos\theta_{CL} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_* \\ y_* \\ z_* \end{bmatrix}$$

$$\begin{bmatrix} U_r \\ V_r \\ W_r \end{bmatrix} = \begin{bmatrix} \cos\theta_{CL} & -\sin\theta_{CL} & 0 \\ \sin\theta_{CL} & \cos\theta_{CL} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} U \\ V \\ W \end{bmatrix}$$

Relative Mean Flow Statistics

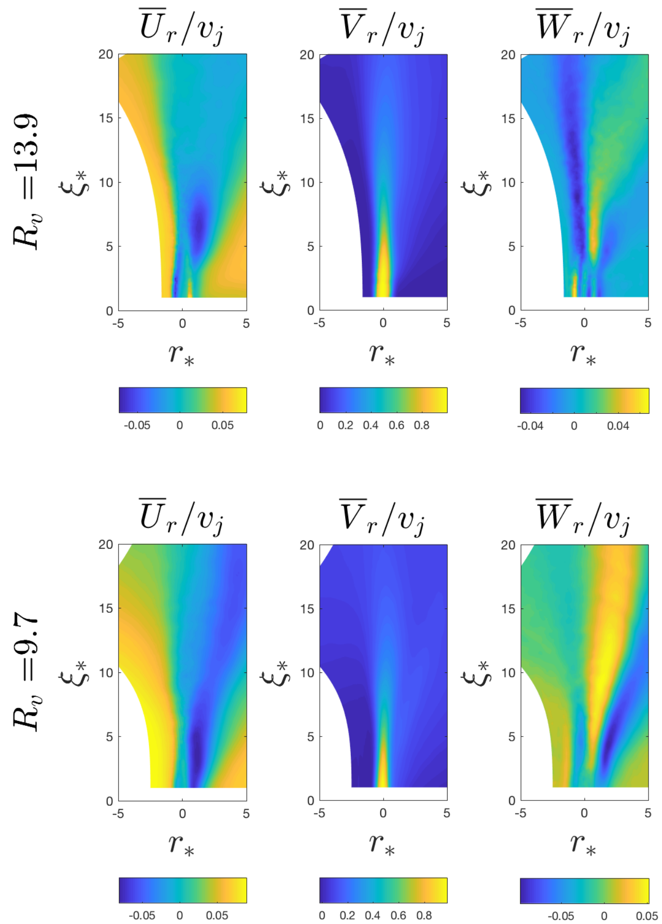


Figure 3. Relative mean flow statistics of instantaneous velocity for R_v=*13.9* (top) and R_v=*9.7* (bottom). Mean velocity is non-dimensionalized by the velocity of the jet, v_j.

Relative Reynolds Stresses

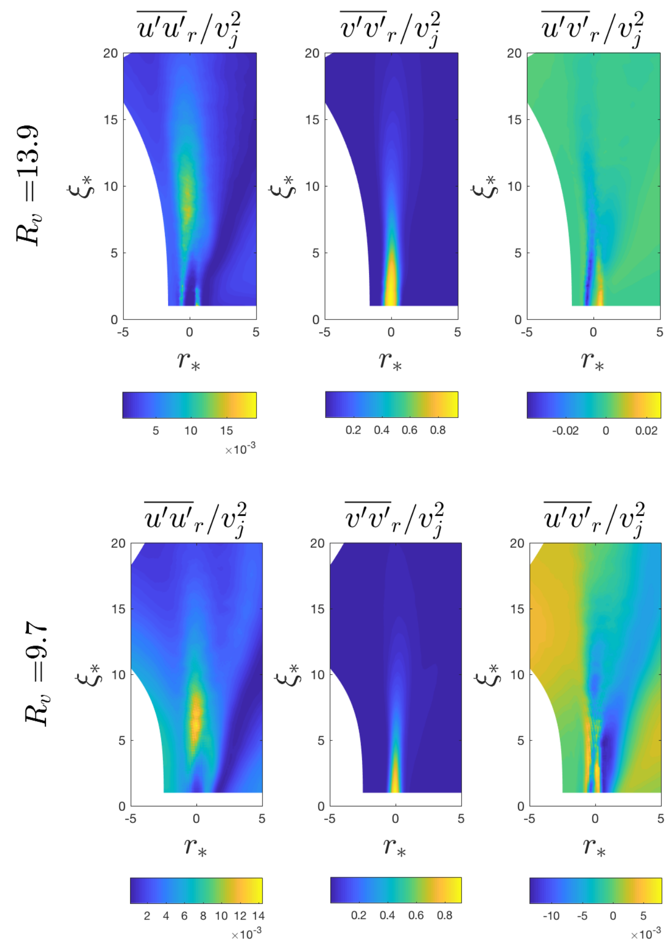
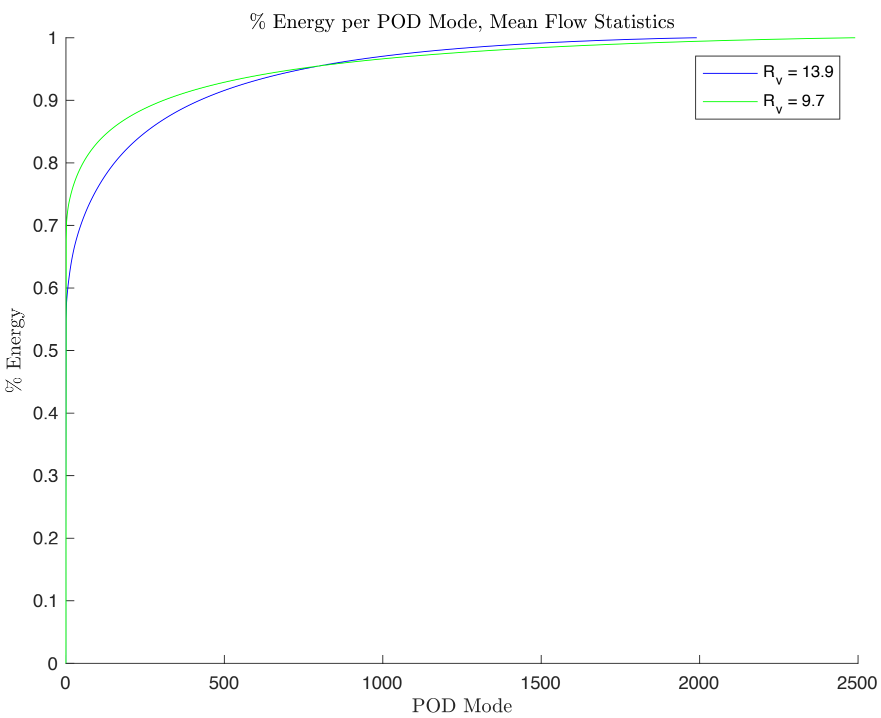


Figure 4. Relative Reynolds stresses , *u'u'*, *v'v'*, and *u'v'* for $R_v=13.9$ (top) and $R_v=9.7$ (bottom). Stress is non-dimensionalized by the velocity of the jet squared, v_j^2.

Percent Energy Per Mode

POD analysis is then applied; below are the resulting percent energy per mode plots



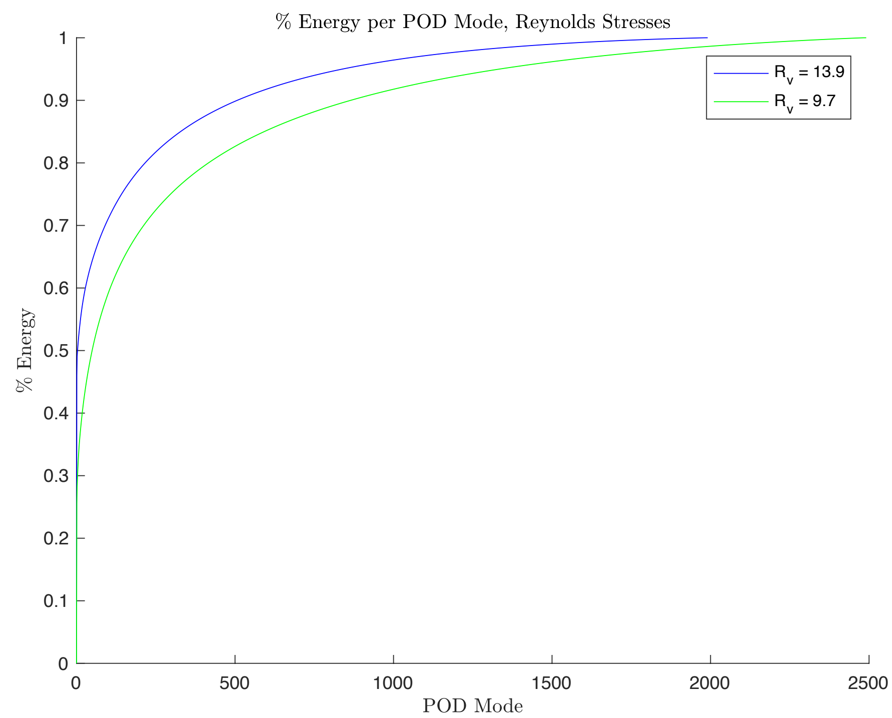


Figure 5. Percent energy versus mode number for the mean flow statistics (left) and Reynolds stresses (right). The total number of modes corresponds to *n*, the total number of snapshots.

POD Modes, Mean Flow Statistics

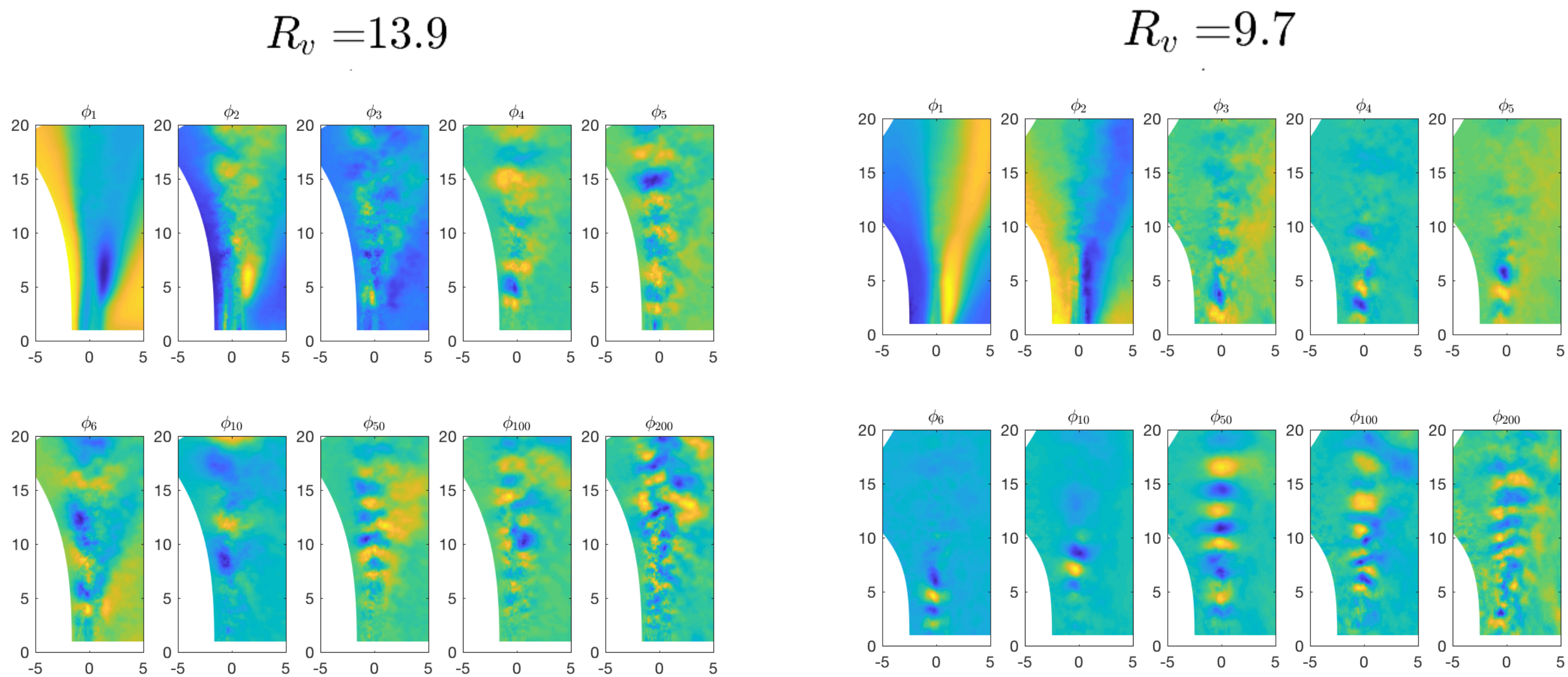


Figure 6 . POD Modes for mean flow statistics in the u-direction, U_r, for R_v=13.9 (left) and R_v=9.7 (right) using modes 1, 2, 3, 4, 5, 6, 10, 50, 100, 200.

POD Modes, Reynolds Stresses

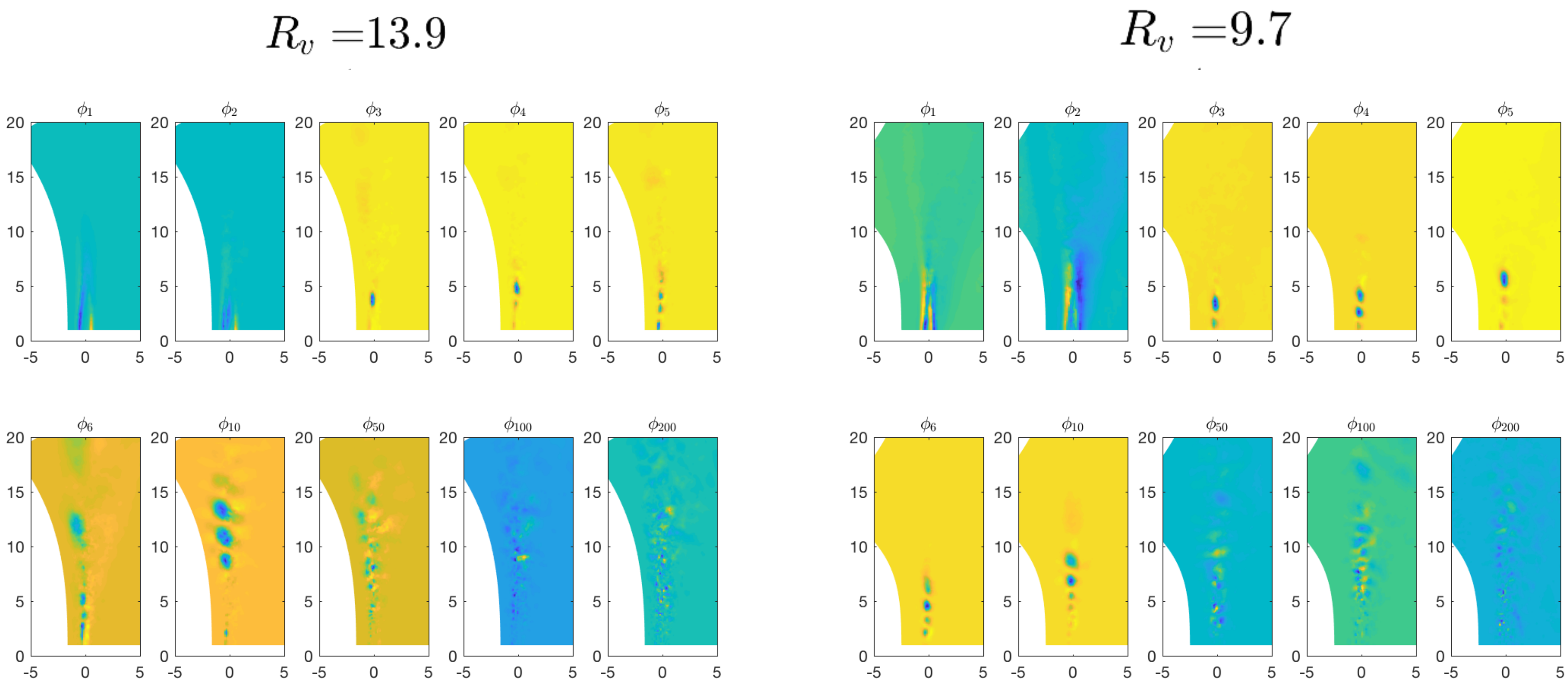


Figure 6 . POD Modes for the shear layer stress, $u'v'_r$, for R_v=13.9 (left) and R_v= 9.7 (right) using modes 1, 2, 3, 4, 5, 6, 10, 50, 100, 200.

Conclusions and Future Work

- ✓ Change of axes showed more complex interactions, removed background noise
- ✓ POD sorted snapshots by energy distribution
- ✓ Modes revealed plume development stages
- ✓ Number of modes to reconstruct fields found

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- ❑ Include higher inflow velocity cases
- ❑ Turn on active grid for increased turbulence intensity
- ❑ Use of other gases for density studies
- ❑ Reconstructions with modes up to 50%, 75%, 90%, 95%, and 100% energy
- ❑ Find shear layer using reconstructions as opposed to actual data

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