High-Fidelity Simulations of Complex High-Speed Flows

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Introduction

- **High-fidelity numerical simulations have been performed to support ongoing projects at FCAAP/FSU:**
  - **Resonance-enhanced micro-actuators that generate pulsed micro-jets for active flow and noise control applications**
  - **Supersonic impinging jets (STOVL aircraft)**
- **Both problems contain complex high-speed flow phenomena at drastically different length scales**
- **Physical experiments are useful but provide limited amount of information**
- **Numerical simulations provide much more detailed information that help towards a better understanding of complex flow physics**

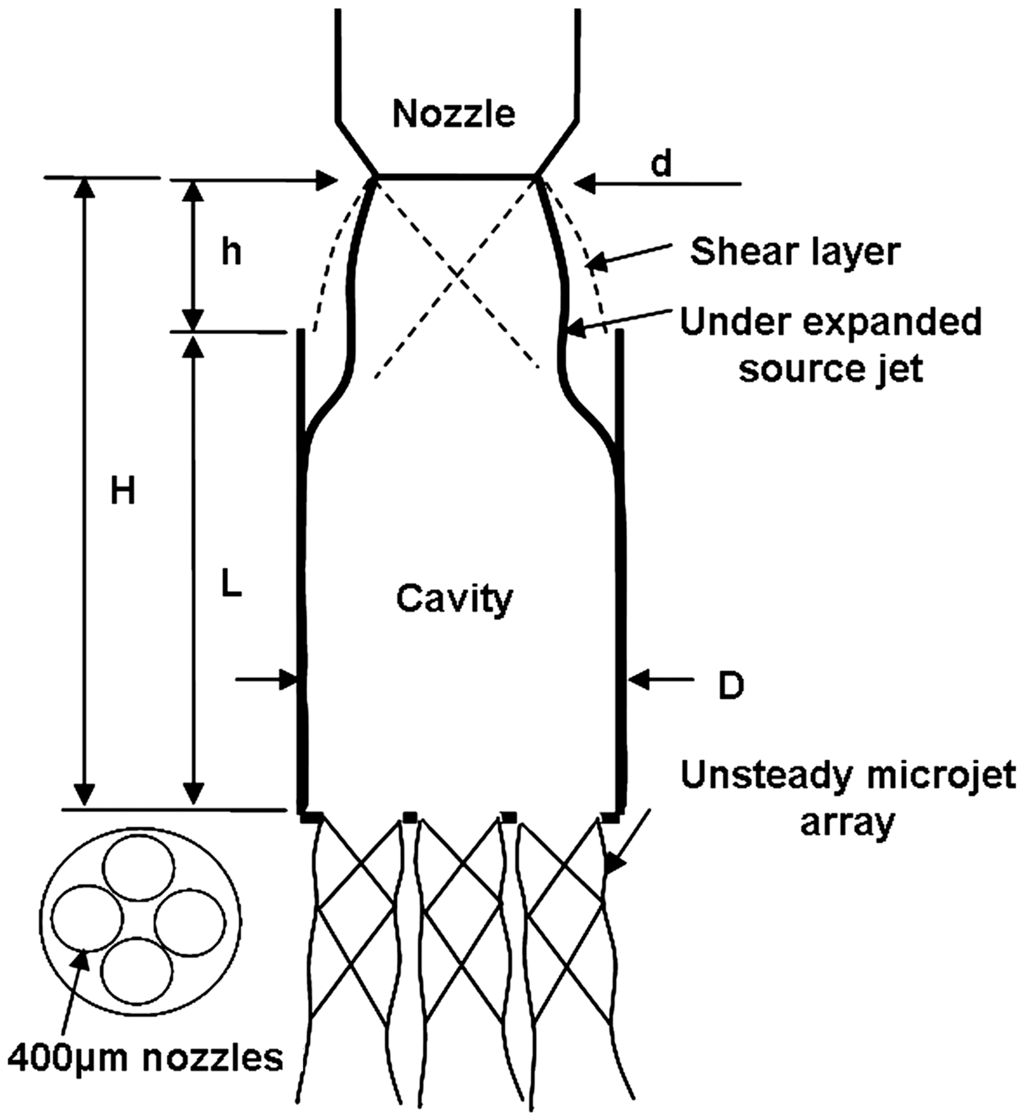
Numerical Methods for High-Fidelity Flow Solver

- Discretized compressible Navier-Stokes equations in generalized curvilinear coordinates
- High-order compact finite difference schemes for spatial derivatives
- High-order implicit spatial filtering for numerical stability
- Explicit and implicit time advancement schemes
- Multi-block and overset grid capability to handle complex geometry
- Parallelization based on domain-decomposition
- Can be run in Direct Numerical Simulation (DNS) and Large Eddy Simulation (LES) modes

Micro-Actuators for Active Flow Control

- **This project is concerned with the development of resonance-enhanced micro-actuators that generate pulsed micro-jets for active flow and noise control applications**
- **High-momentum micro-jets are injected into the primary flow at critical points to achieve the control objective**
- **Goal is to further increase control effectiveness by manipulating the steady and unsteady components of the micro-jet**
- **Resonance-enhanced actuators provide a capability to adjust micro-jet pulse frequency and amplitude for the control application of interest**

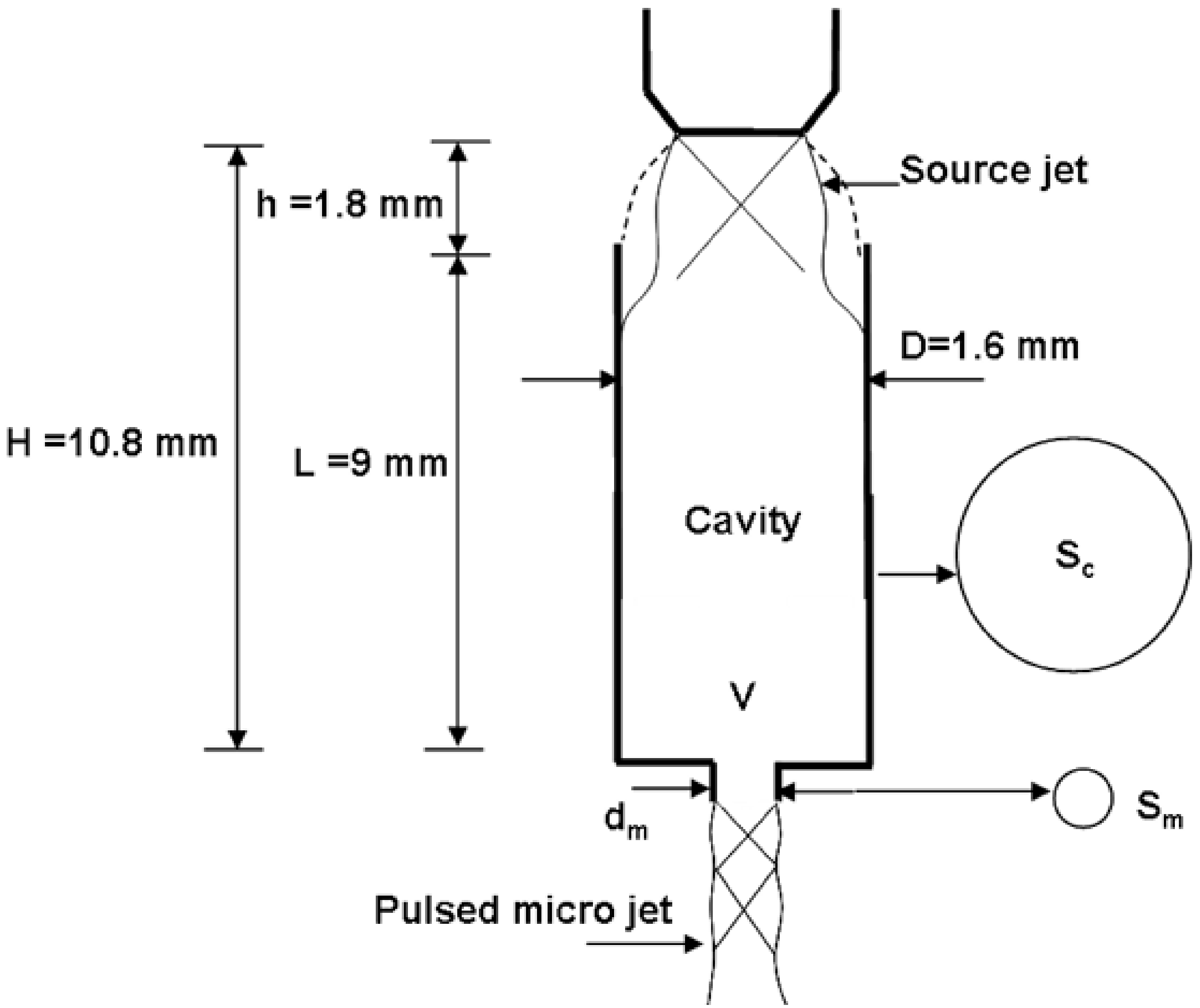
Schematic of First-Generation Resonance-Enhanced Micro-Actuator



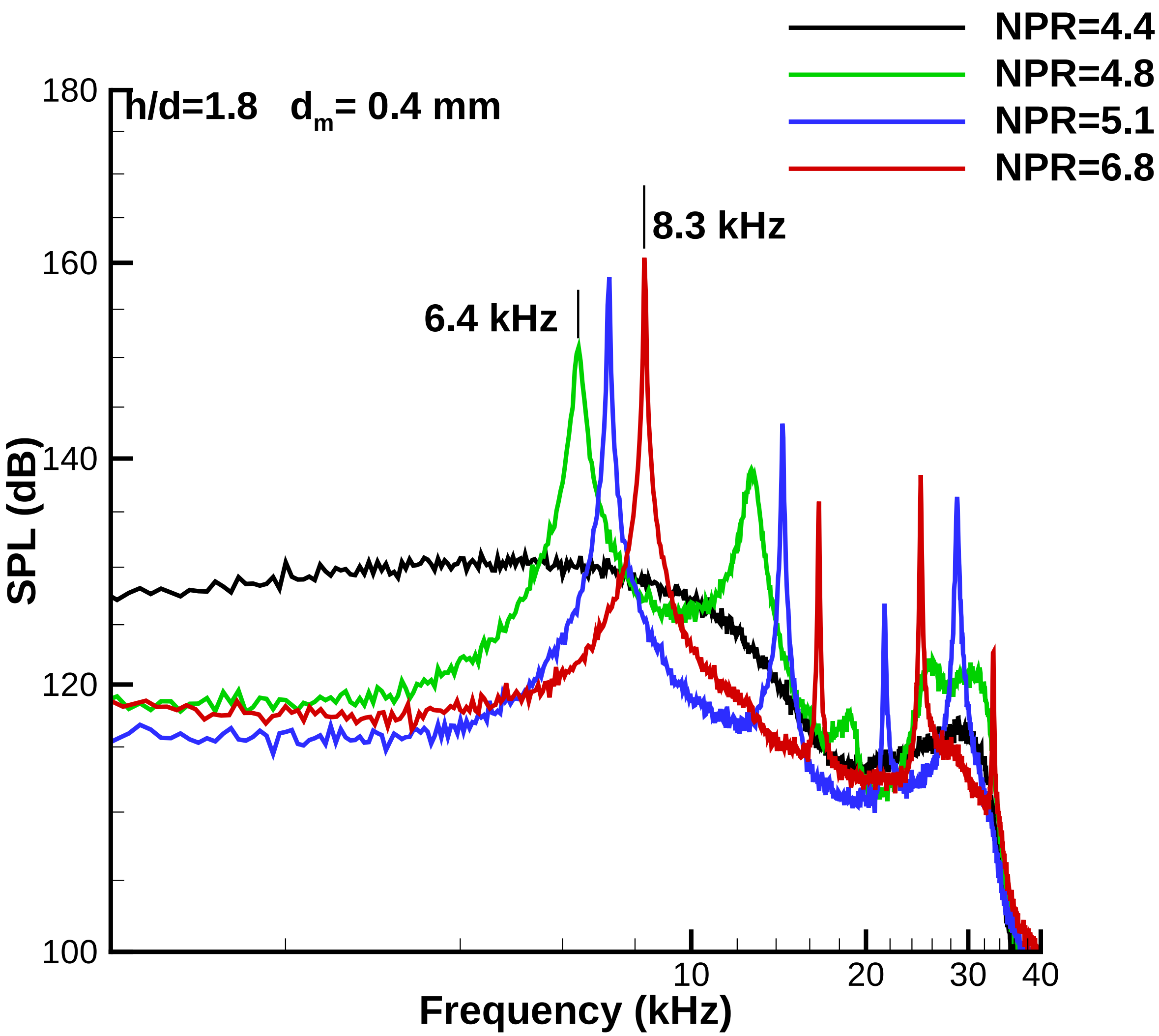
Micro-Actuator Resonance Frequency

- **Simulations reveal the complex details of the "aero-acoustic" resonance, which involves a periodic filling and discharging of actuator cavity volume**
- **Actuator resonance frequency is determined by how quickly the actuator cavity fills and discharges**
- **Resonance frequency is dependent on actuator dimensions as well as incoming source jet conditions**
- **Micro-jet pulse frequency is the same as the actuator resonance frequency**

Single-Orifice Micro-Actuator Chosen for Simulation



Experimental Spectra of Micro-Jet Generated by Single-Orifice Micro-Actuator



Single-Orifice Micro-Actuator Simulation

- **Length scale = source jet nozzle inner diameter, $d = 1$ millimeter**
- **Velocity scale = source jet exit speed ≈ 343 meters/second**
- **Reynolds number, $Re_d = U_j d/\nu_j \approx 37,000$**
- **Source jet nozzle pressure ratio, $\mathrm{NPR} = 6.8$**
- **Peak Mach number in actuator flowfield ≈ 1.8**
- **Highly compressible and unsteady micro-scale flow at relatively low Reynolds number**
- **Fully 3-D large eddy simulation (LES) using 92 million grid points total**
- **720 processor cores running in parallel**
- **About 45 days of total run time**

Single-Orifice Micro-Actuator Simulation

- **The most relevant time scale of the problem is the period of the "aero-acoustic" resonance, which involves a periodic filling and discharging of actuator cavity volume**
- **For the given operating conditions at $\mathrm{NPR} = 6.8$, the simulation shows that one cavity fill-and-discharge cycle takes place over roughly 120.5 microseconds**
- **This corresponds to a resonance frequency of about 8.3 kHz ($= 1/120.5$ microseconds), same as the fundamental tone frequency observed in the experimental spectrum for $\mathrm{NPR} = 6.8$**

Single-Orifice Micro-Actuator Simulation

- **Period of the resonance cycle is about 120.5 microseconds**
- **Simulation time step corresponds to a physical time step of 7.3 nanoseconds**
- **Simulation time step is very small because the presence of strong shocks in the flowfield makes the problem very "numerically stiff"**
- **Very small time steps are necessary to maintain numerical stability**
- **Implicit time stepping allows maximum Courant-Friedrichs-Lewy (CFL) number of 8 to 9**
- **Length of simulation statistical sample size corresponds to 3 milliseconds (about 25 resonance cycles)**

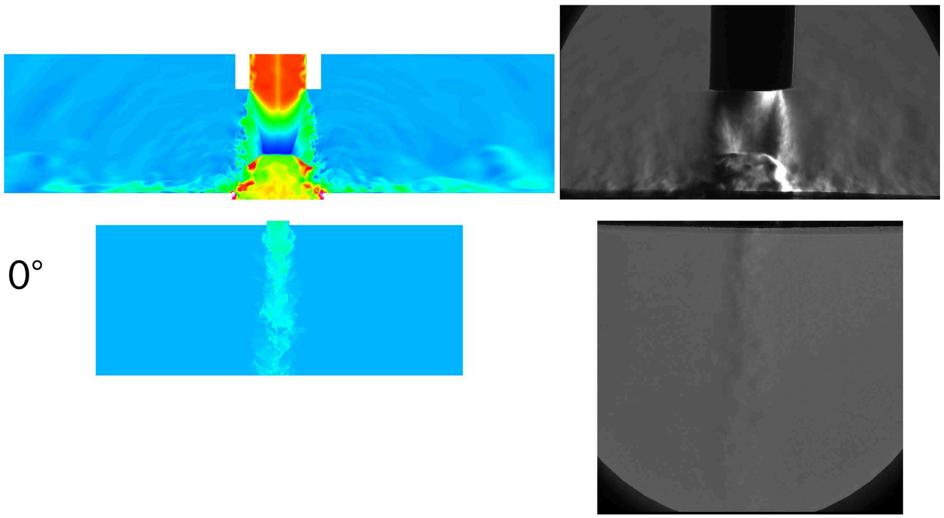
Simulation Animations

- **Actuator simulation animations and comparison with experimental measurements are available at the following link:**

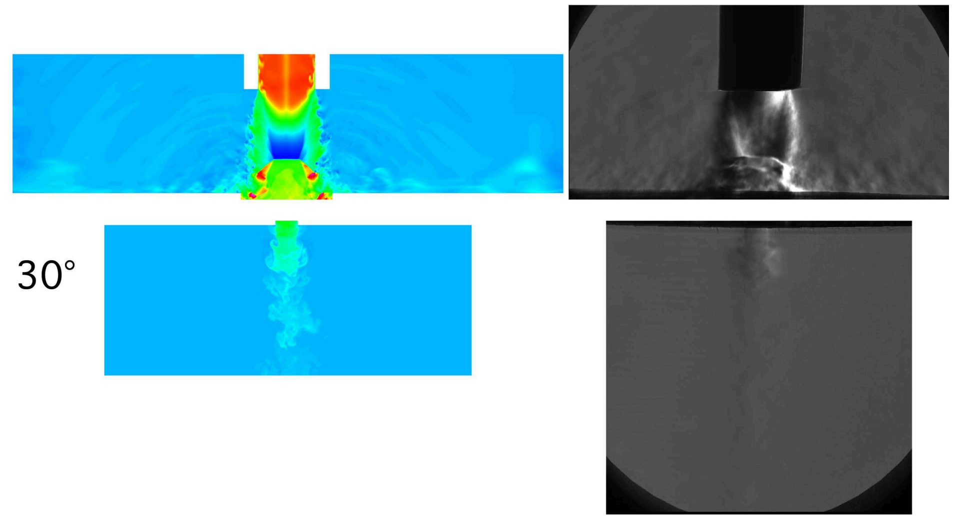
  http://www.math.fsu.edu/~auzun/SingleOrificeActuator/

Qualitative Comparison with Experiment

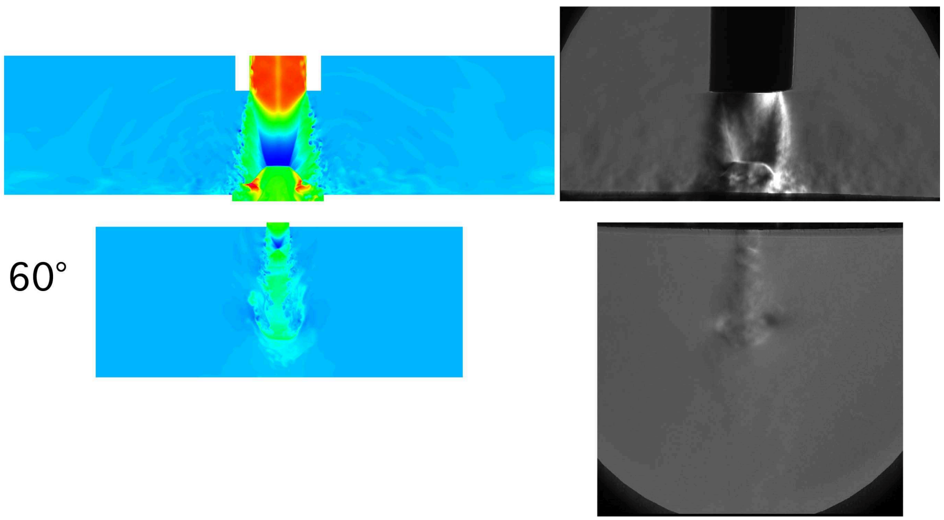
- We make a qualitative comparison between simulation predicted flowfield and experimental micro-schlieren measurements over one cavity fill-and-discharge cycle
- One periodic cycle (which covers 360 degrees) is divided into 12 equally spaced snapshots
- The phase difference between two successive snapshots is 30 degrees
- In the experiment, the cavity is not transparent and thus the cavity flow cannot be visualized
- We omit the cavity region in the comparison



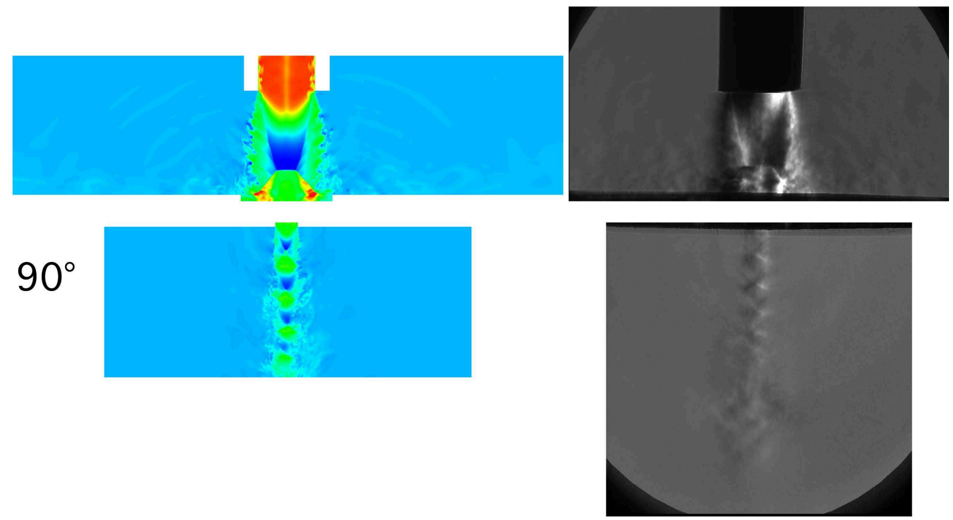
(a) Phase angle = 0°



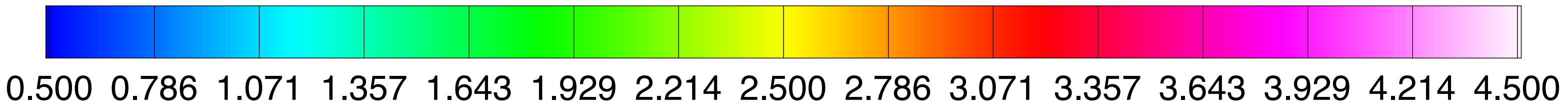
(b) Phase angle = 30°



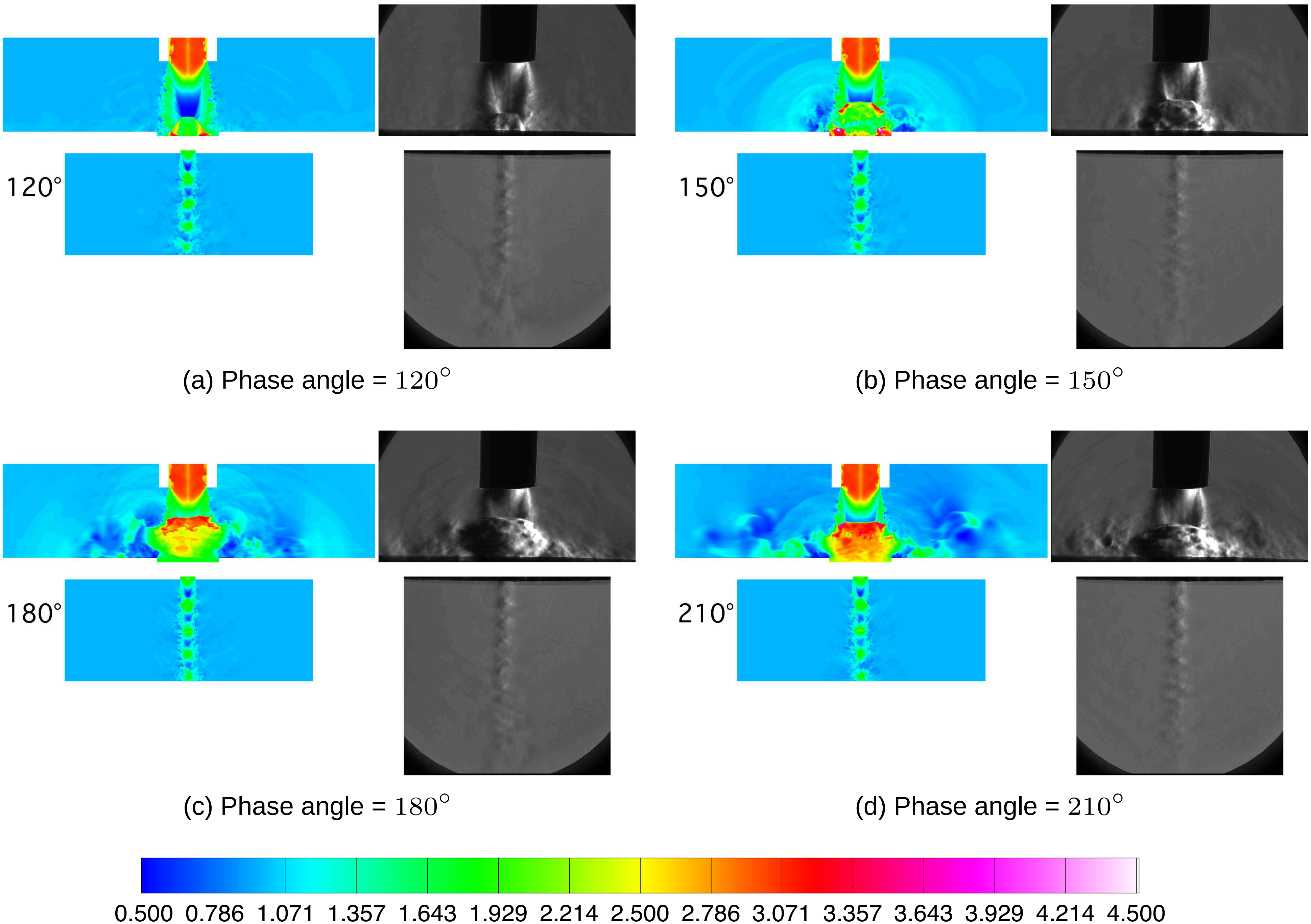
(c) Phase angle = 60°



(d) Phase angle = 90°



Color map represents normalized density, $\rho/\rho_{\textbf{ambient}}$



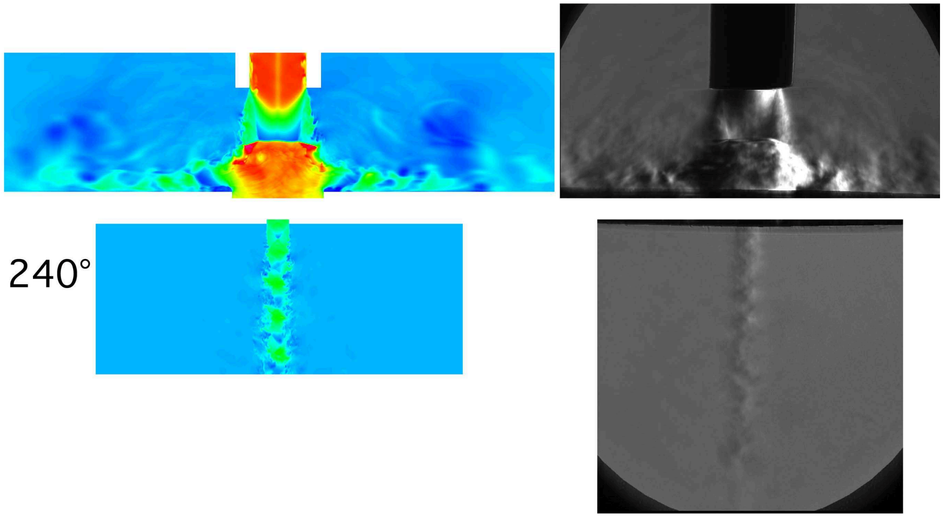
(a) Phase angle = 120°

(b) Phase angle = 150°

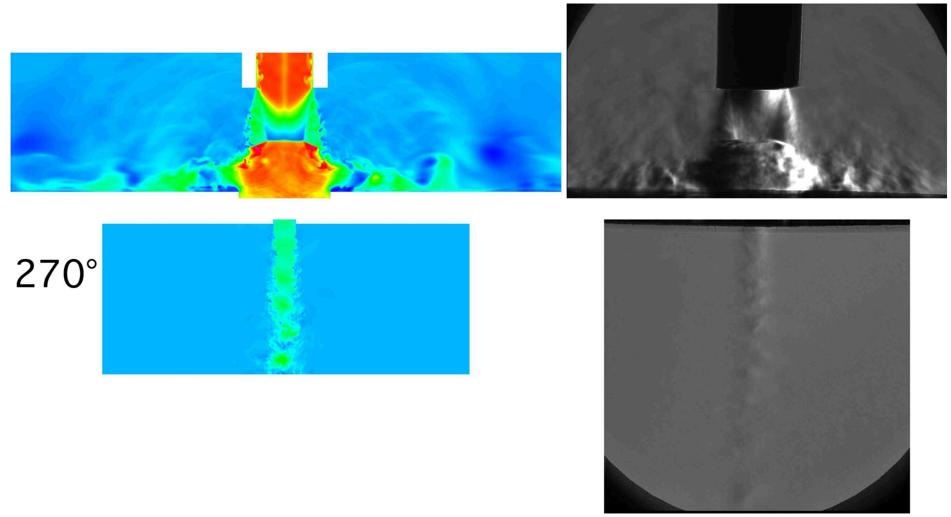
(c) Phase angle = 180°

(d) Phase angle = 210°

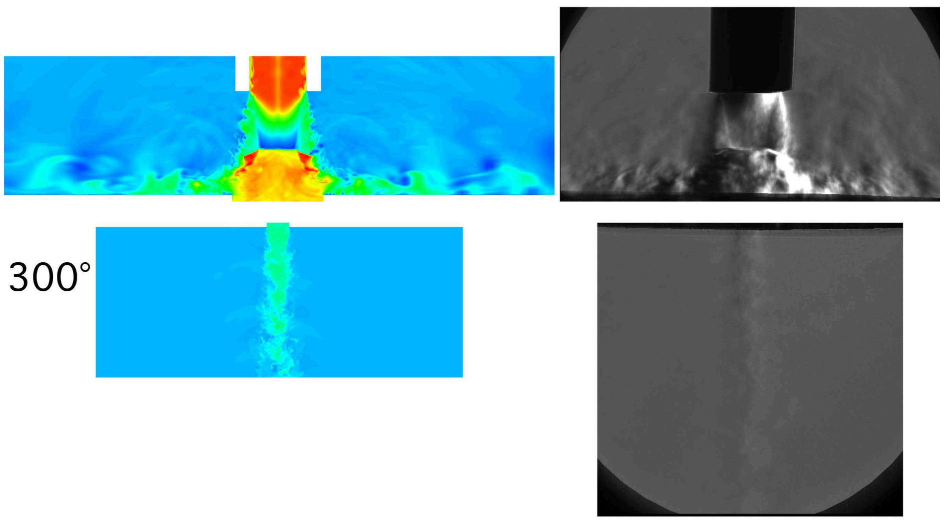
Color map represents normalized density, $\rho/\rho_{\mathbf{ambient}}$



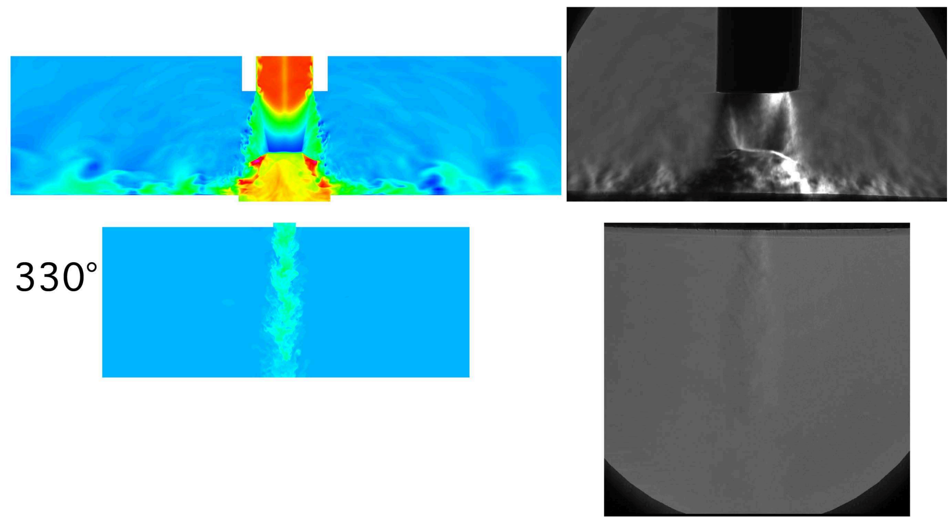
(a) Phase angle = 240°



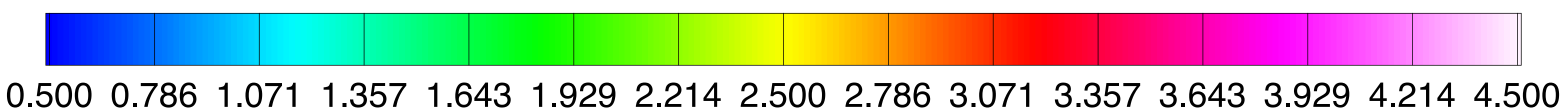
(b) Phase angle = 270°



(c) Phase angle = 300°



(d) Phase angle = 330°

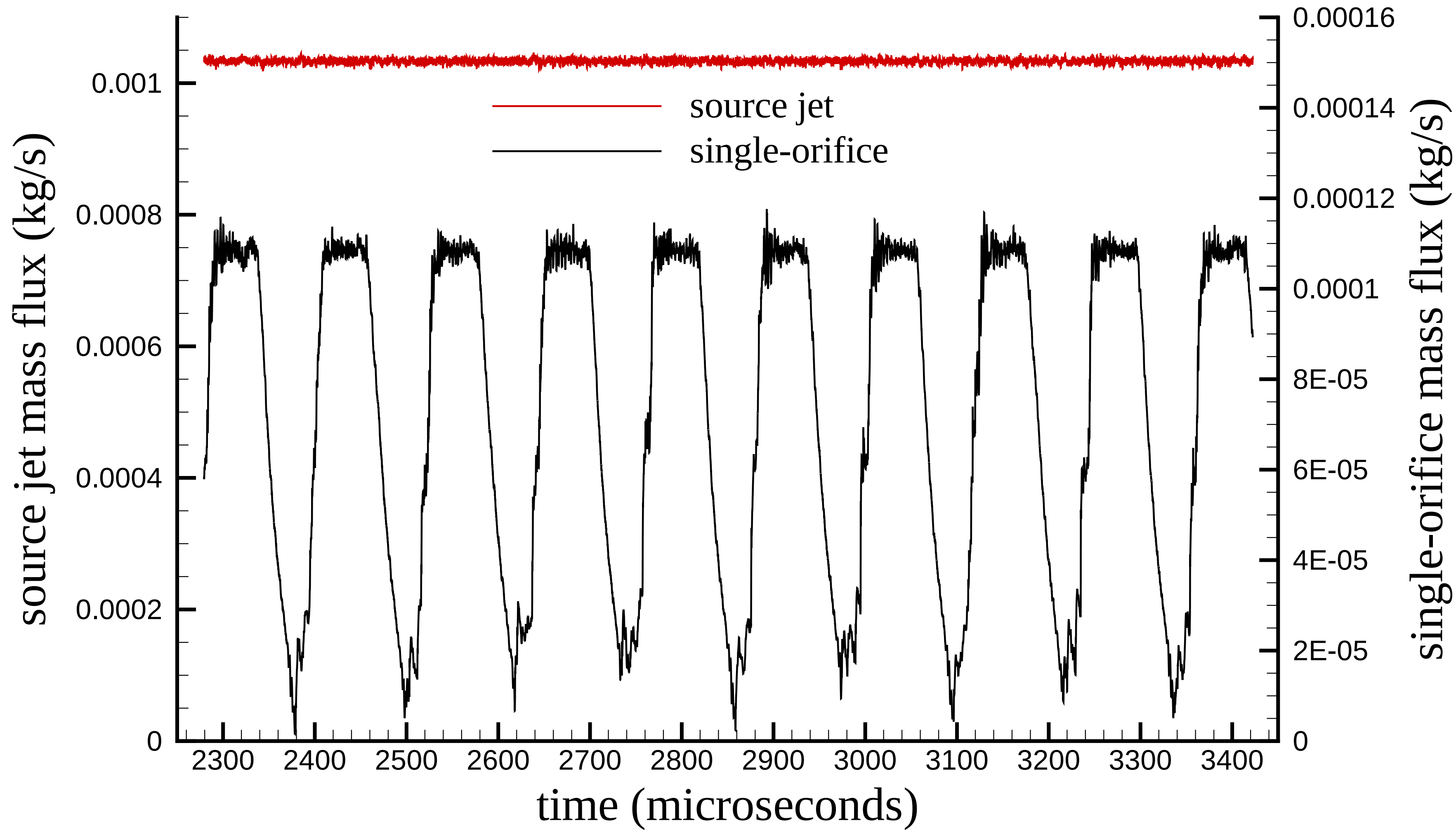


Color map represents normalized density, $\rho/\rho_{\mathbf{ambient}}$

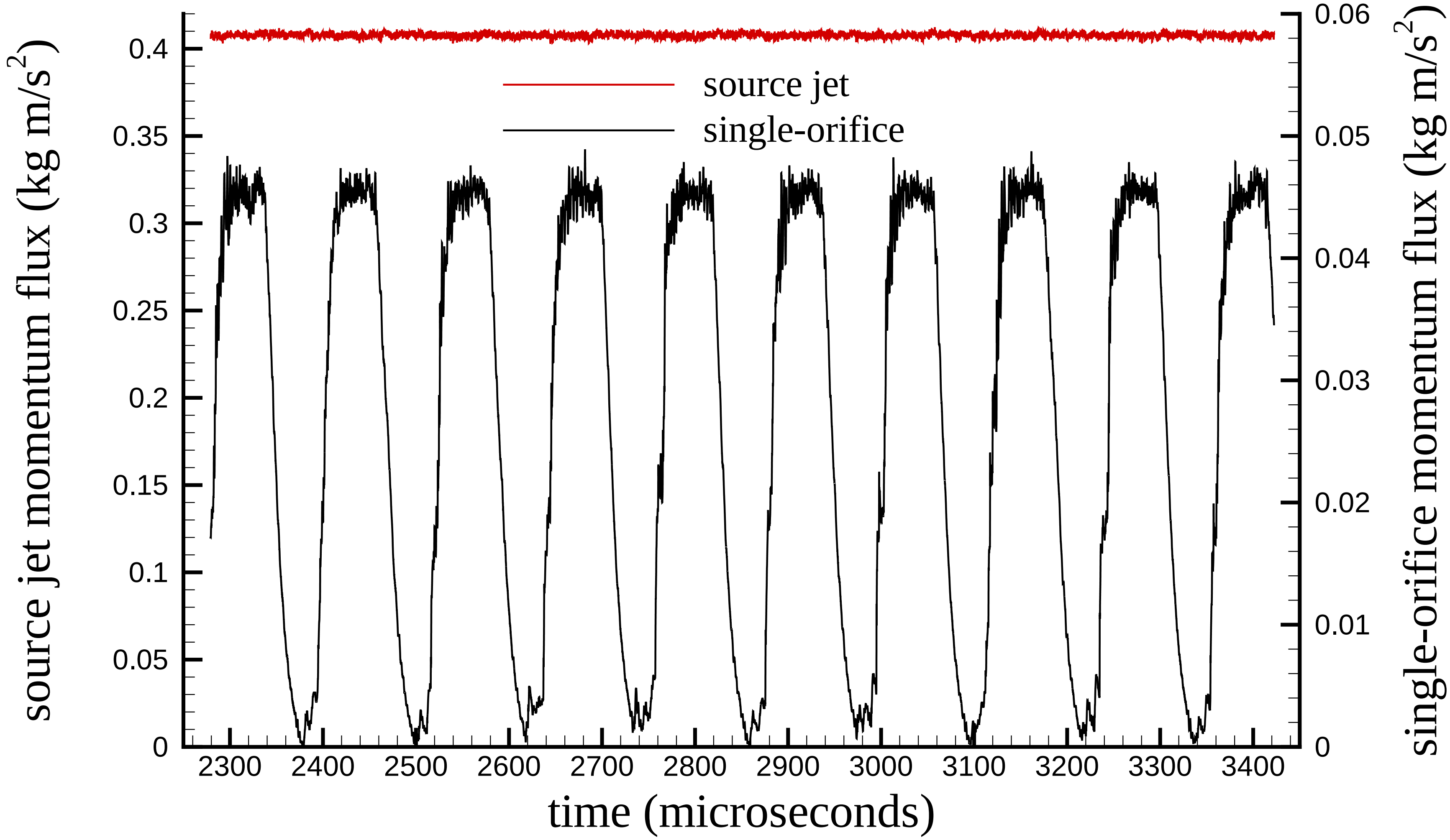
Performance and Efficiency Metrics

- **Some useful metrics can be defined as:**
  - **Ratio of peak mass flow rate through orifice to mass flow rate of source jet ($\approx$ 10 %)**
  - **Ratio of peak momentum flux through orifice to momentum flux of source jet ($\approx$ 11 %)**
  - **Duty cycle of pulsed microjet ($\approx$ 40 %)**

Mass Flux Time History

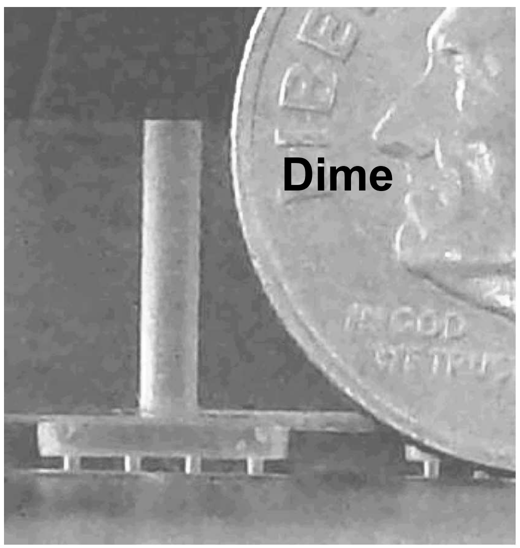


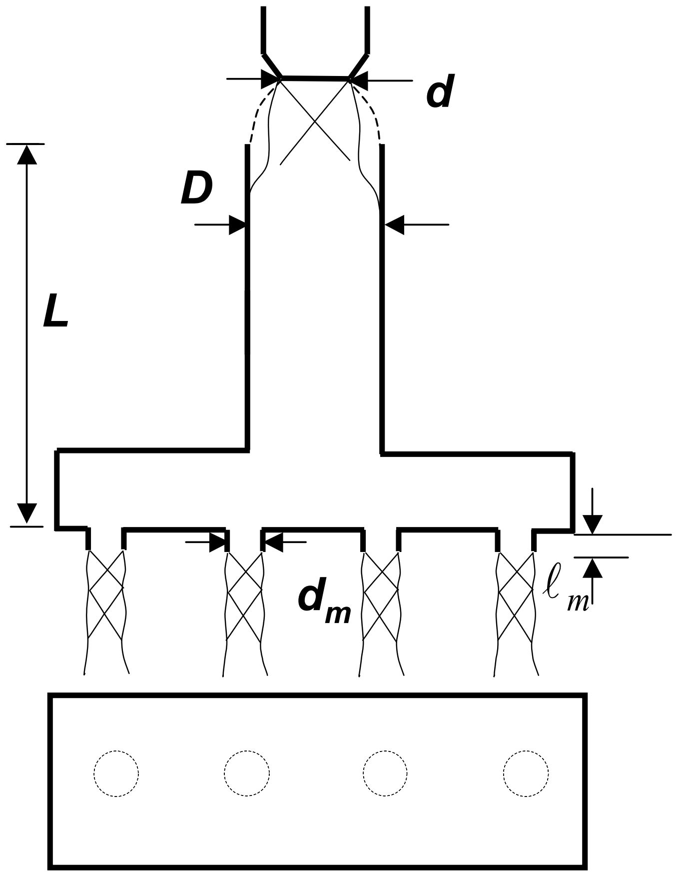
Momentum Flux Time History



Multiple-Orifice Micro-Actuator Design

- **To utilize a greater portion of the source jet flow, multiple orifices can be placed at cavity bottom**

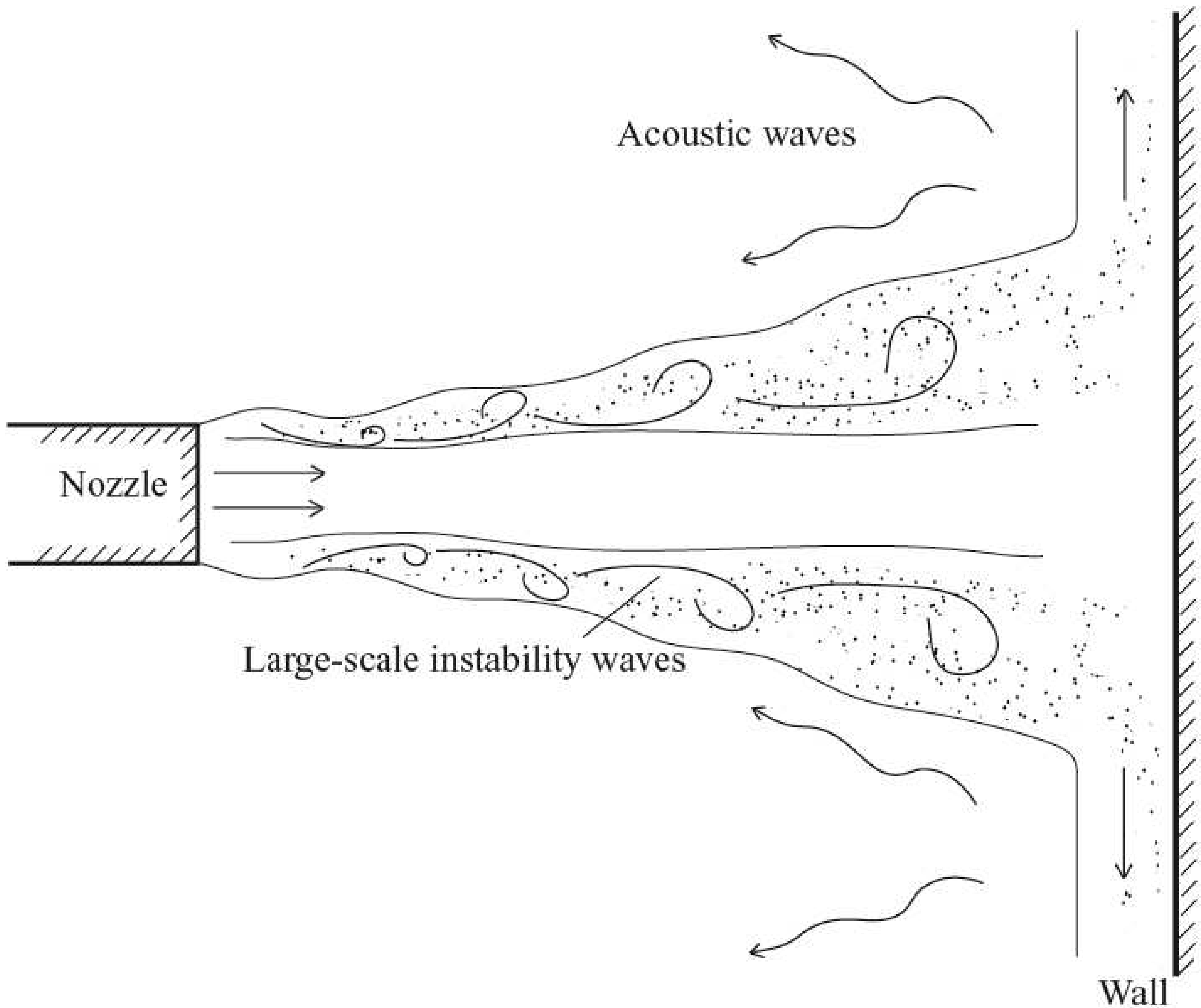




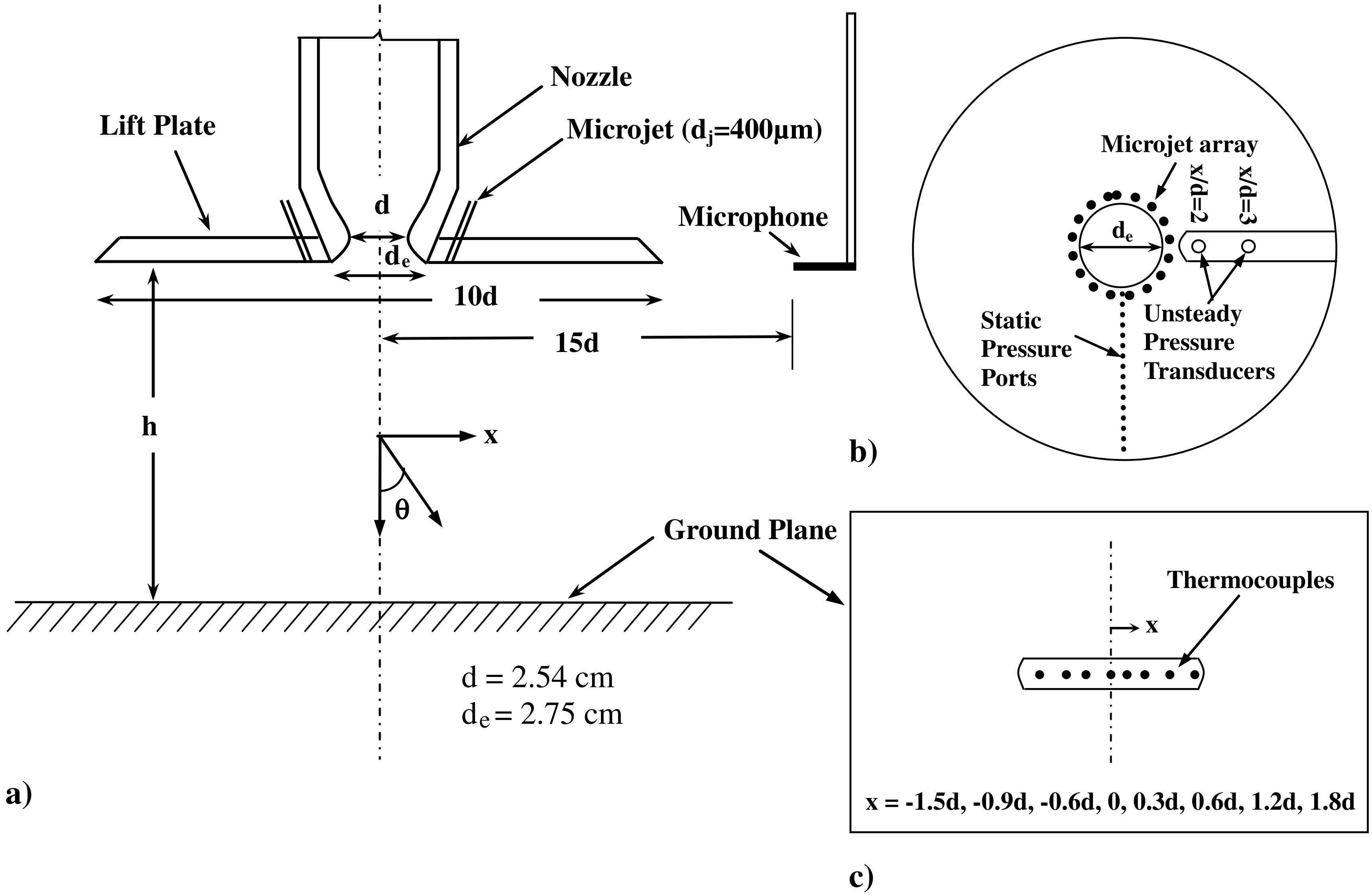
Supersonic Impinging Jets

- An important problem for short take-off and vertical landing (STOVL) aircraft
- High-speed jet impingement on landing surface leads to many adverse effects such as:
  - High levels of unsteady pressure loads on landing surface and nearby structures
  - Significantly higher noise levels than conventional take-off aircraft
  - Aircraft lift loss during hover
  - Erosion of landing surface due to high jet exhaust temperature
- Resonance dominated flowfield that is governed by a well-known feedback loop

Schematic of Feedback Loop



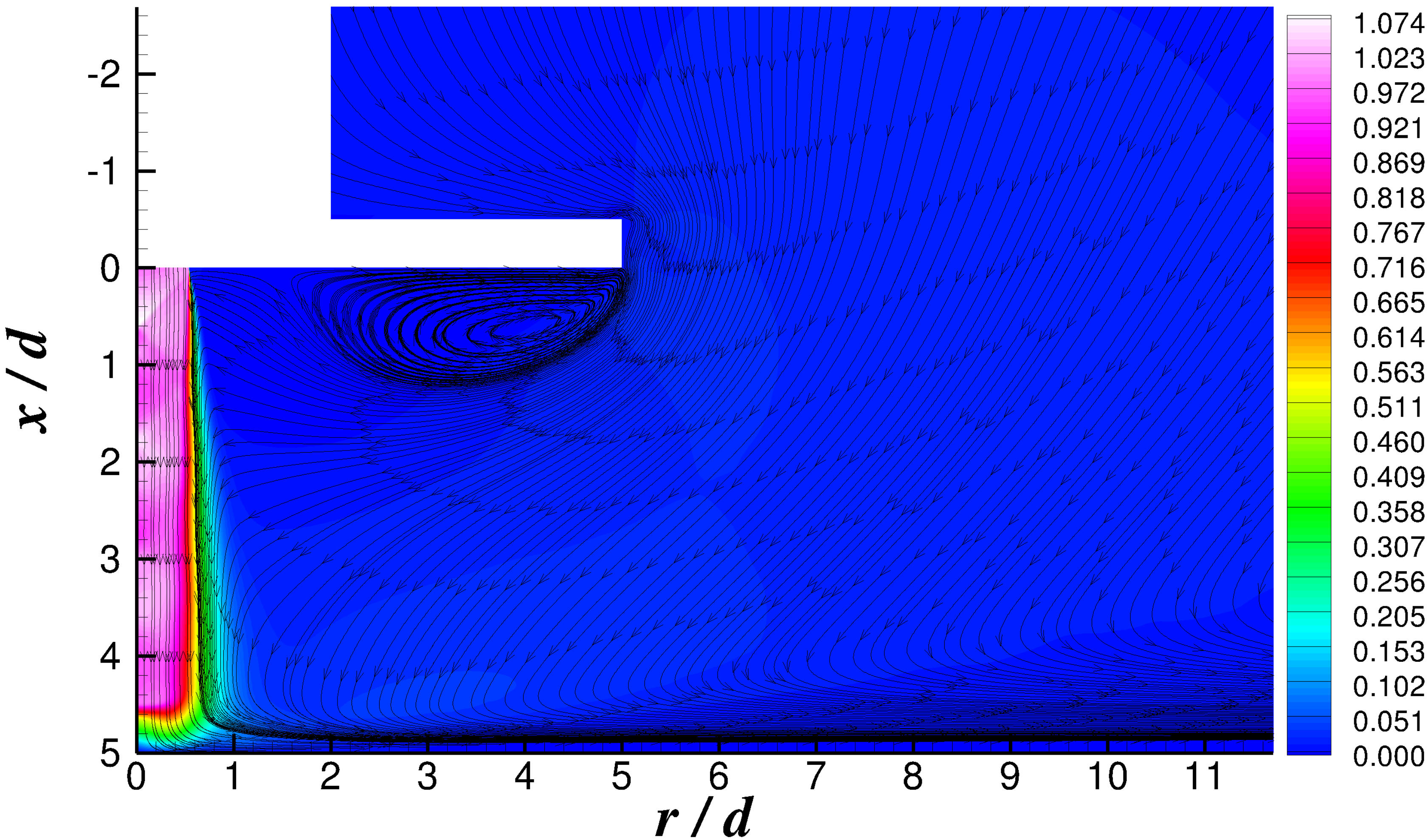
Schematic of Experimental Setup



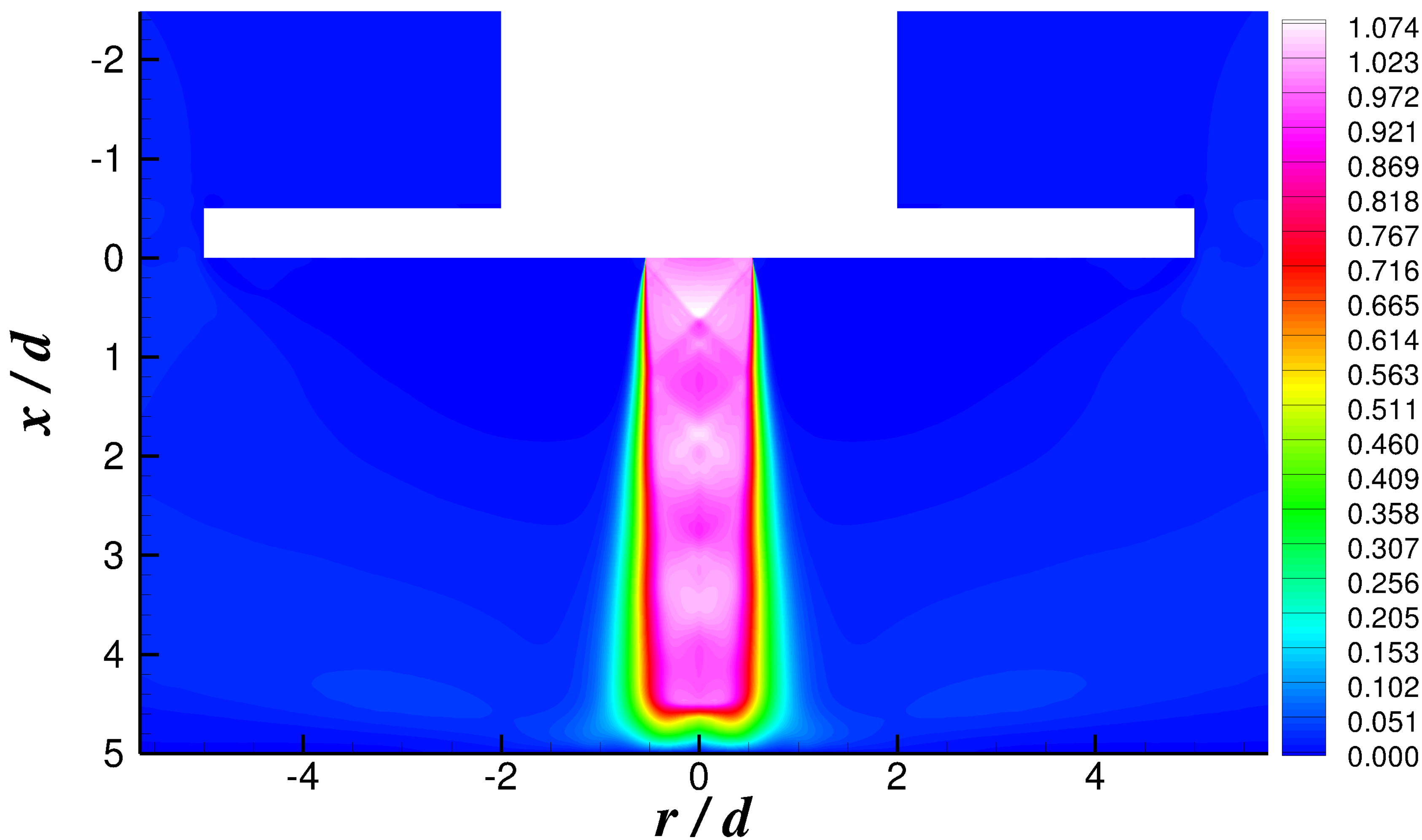
Near-Ideally Expanded Mach 1.5 Uncontrolled Impinging Jet Simulations

- **Near-ideally expanded isothermal and heated jet simulations matching experimental cases**
- **Reynolds number range** $\approx 0.9 \times 10^6$ **to** 1.3×10^6
- **Ratio of jet impingement distance to nozzle throat diameter,** $h/d = 5$
- **Experimental setup is duplicated in the simulations**
- **Laminar nozzle inflow conditions**
- **Fully 3-D LES using** 200 **million grid points**
- **Several months of total run time using about** 1200 **processor cores in parallel**

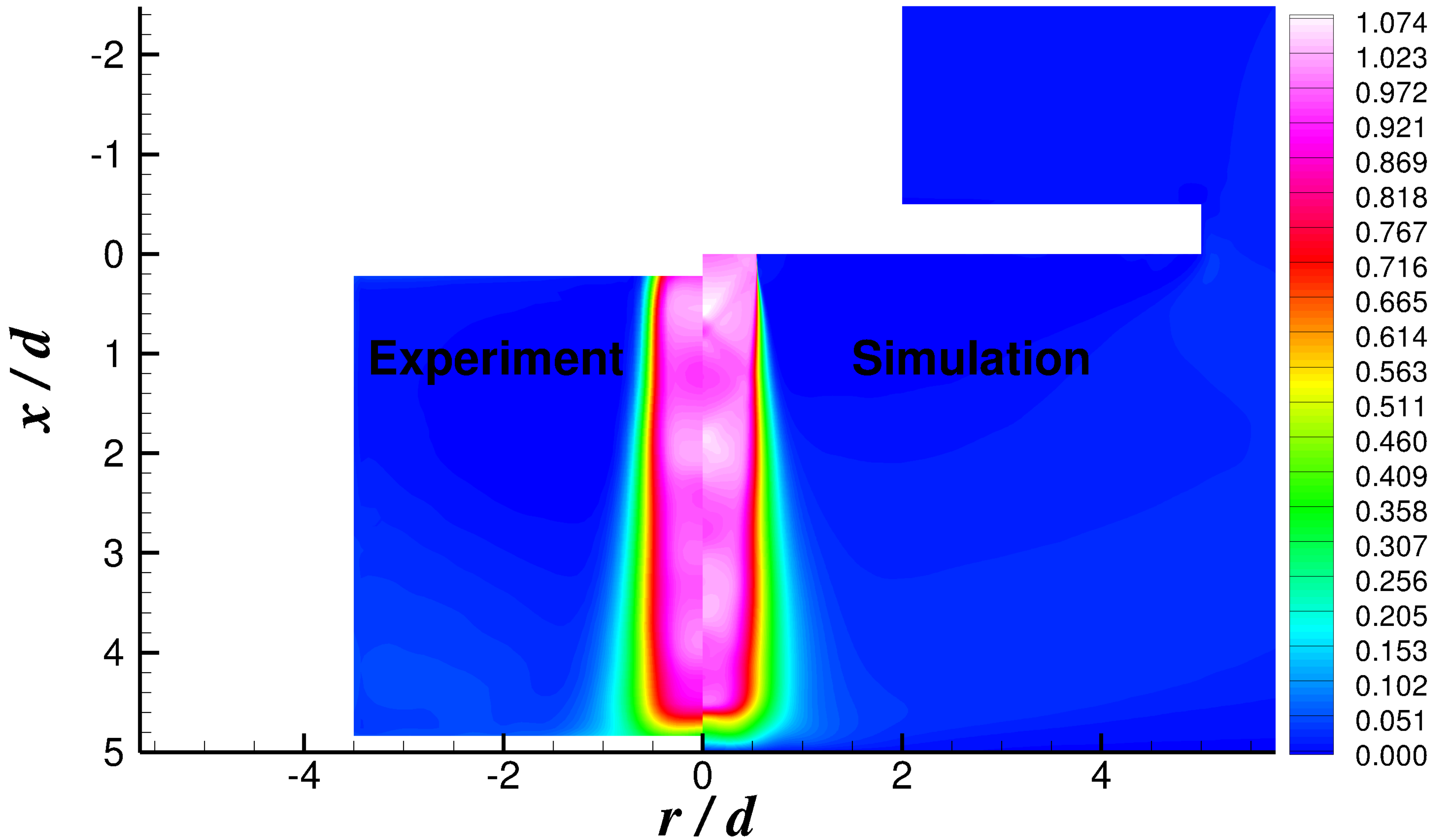
Isothermal Mach 1.5 Jet Mean Flow Streamlines



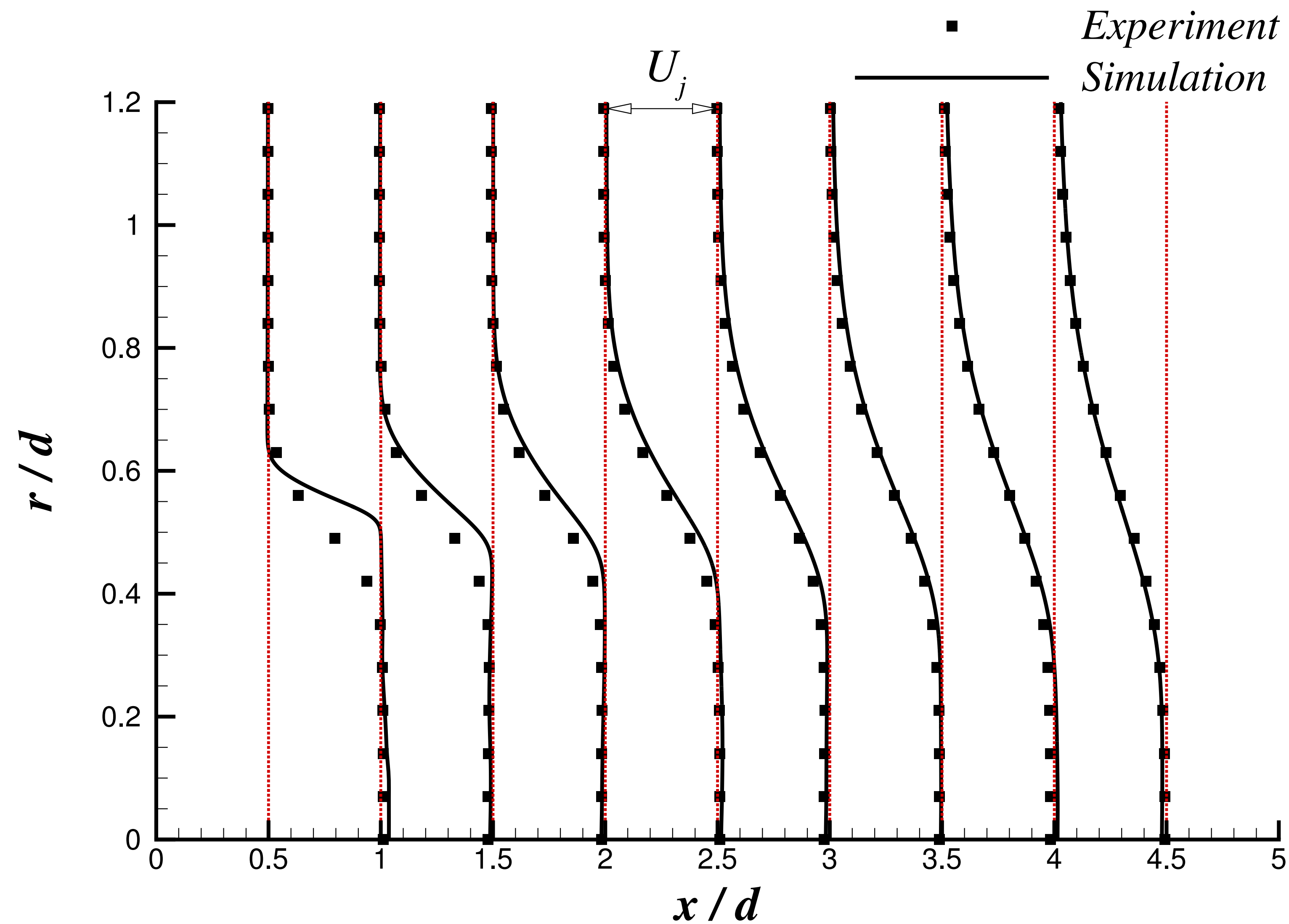
Isothermal Mach 1.5 Jet Normalized Mean Axial Velocity (U/U_j) Contours



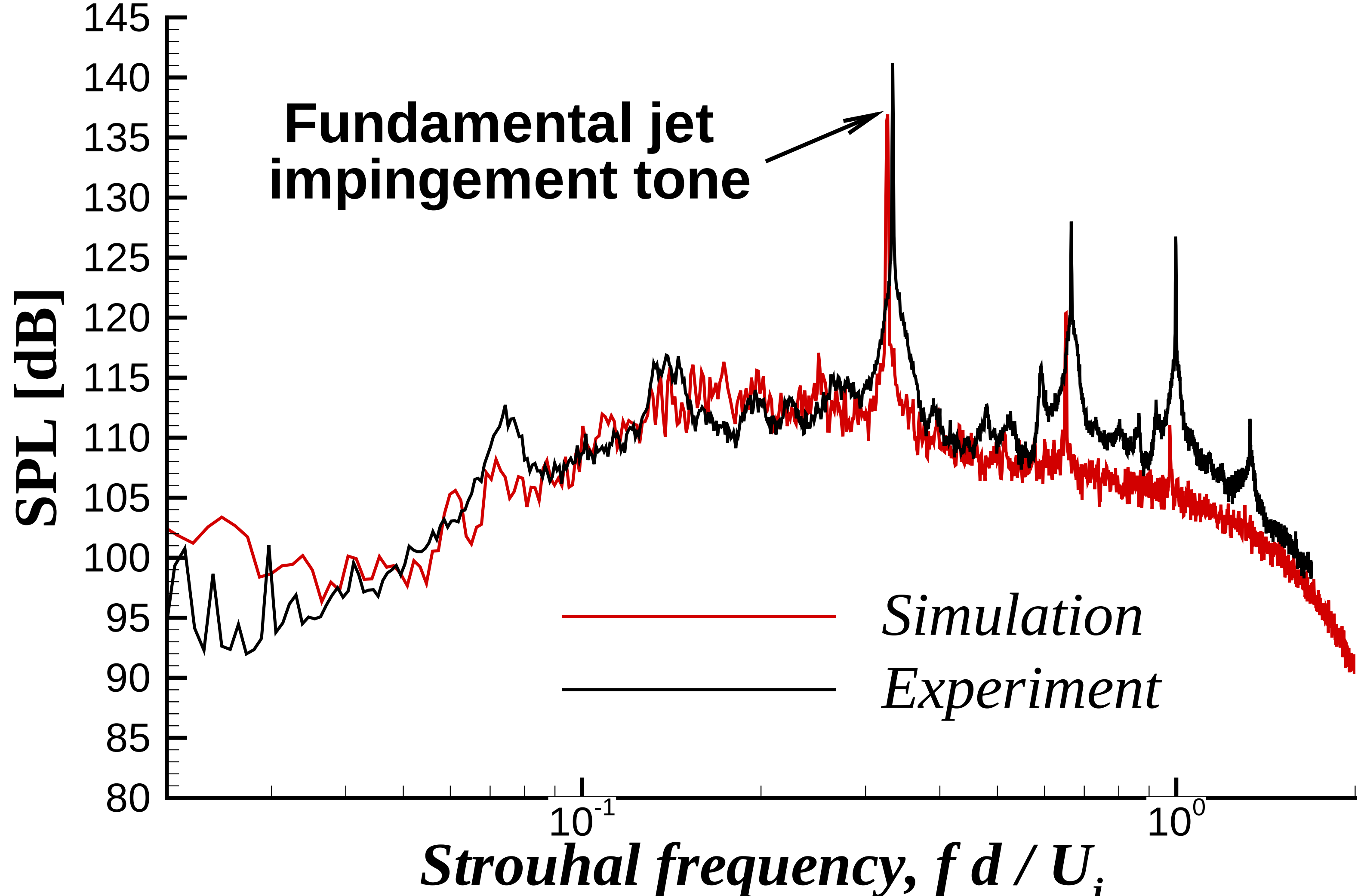
Heated Mach 1.5 Jet Normalized Mean Axial Velocity (U/U_j) Contours



Comparison of Normalized Mean Axial Velocity Profiles for Heated Mach 1.5 Jet



Comparison of Microphone Noise Spectra for Heated Mach 1.5 Jet



Identification of Coherent Structures

- **Dynamic mode decomposition (DMD) has been utilized to identify the coherent structures that are responsible for intense tonal generation in supersonic impinging jets**
- **DMD (Schmid, JFM 2010) is a technique that allows the extraction of dynamically relevant flow features from a uniformly sampled data sequence, available from the simulations**
- **We utilize a total of nearly 800 flowfield snapshots with a uniform $\Delta t = 0.25 d/U_j$ for DMD analysis**

Dynamic Mode Decomposition

- **The unsteady flowfield is represented as a superposition of a number of dynamic modes:**

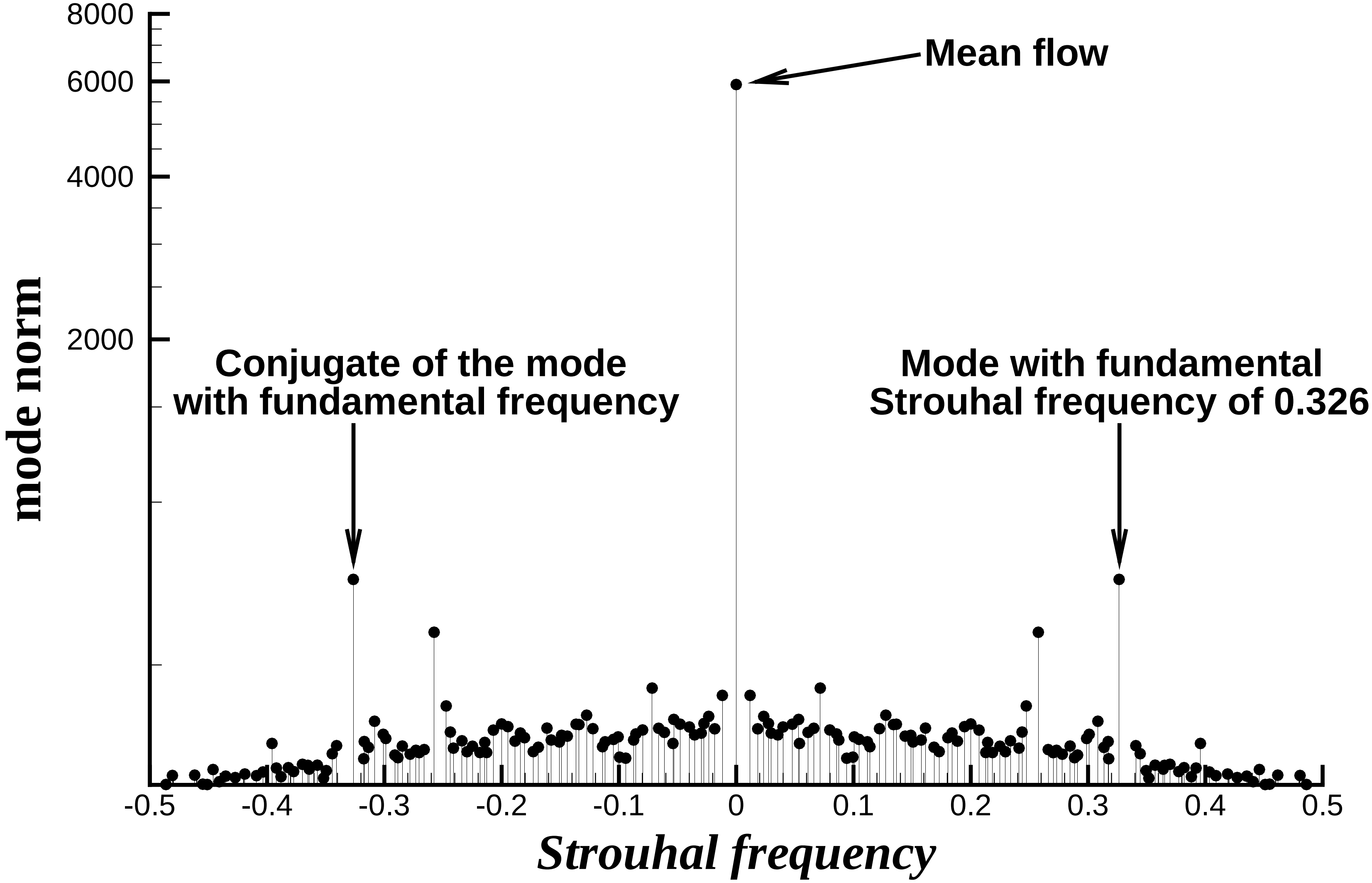
$$\mathbf{V}(x, y, z, t) = \sum_{k=1}^{N-1} \Phi_k(x, y, z) \cdot T_k(t)$$

where

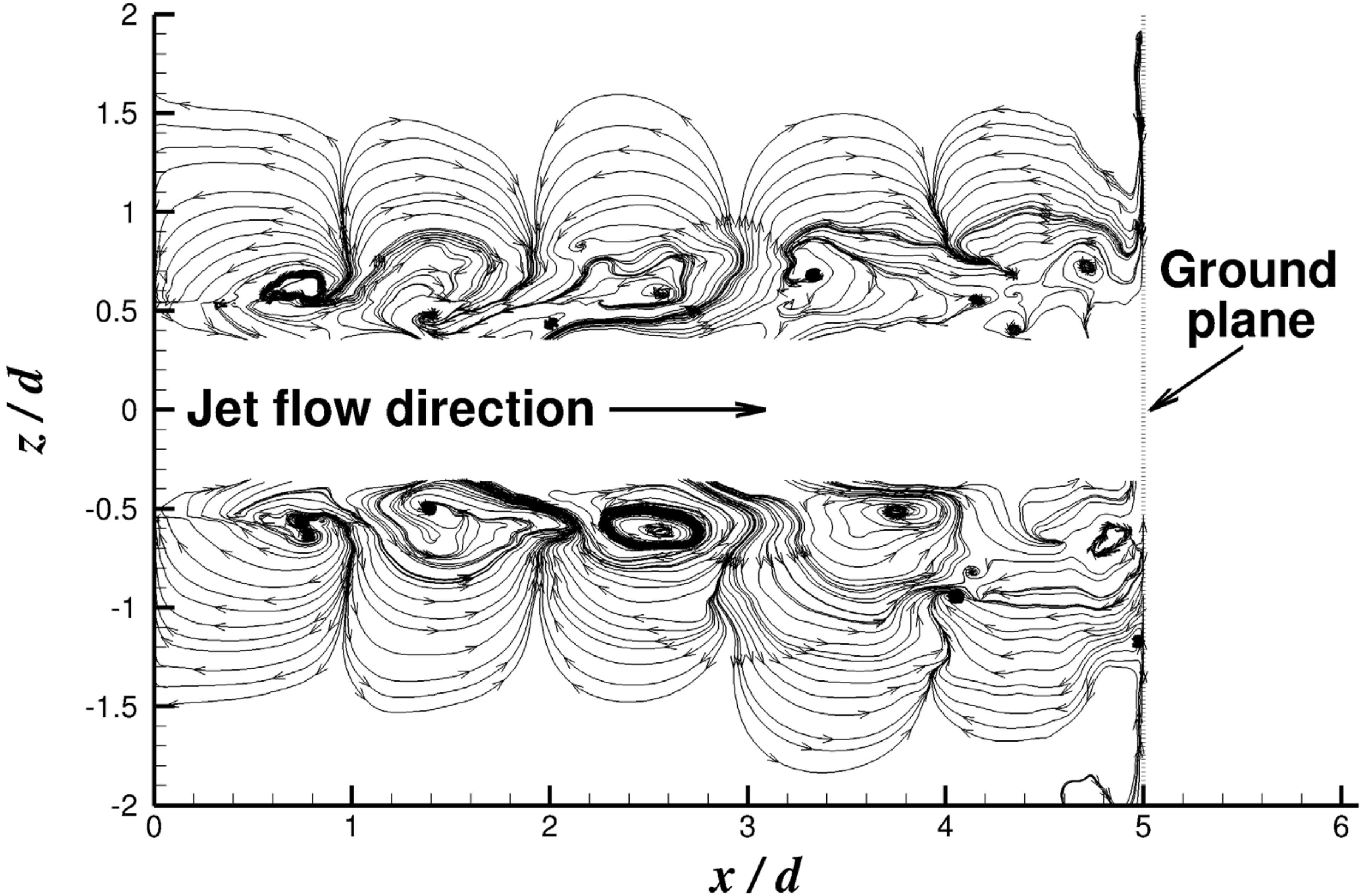
- N **is the total number of flowfield snapshots**
- $\mathbf{V}(x, y, z, t)$ **is the real-valued unsteady flowfield**
- $\Phi_k(x, y, z)$ **is the complex-valued** k^{th} **mode**
- $T_k(t)$ **is the temporal amplitude of** Φ_k

- **Dynamic modes occur in complex-conjugate pairs**

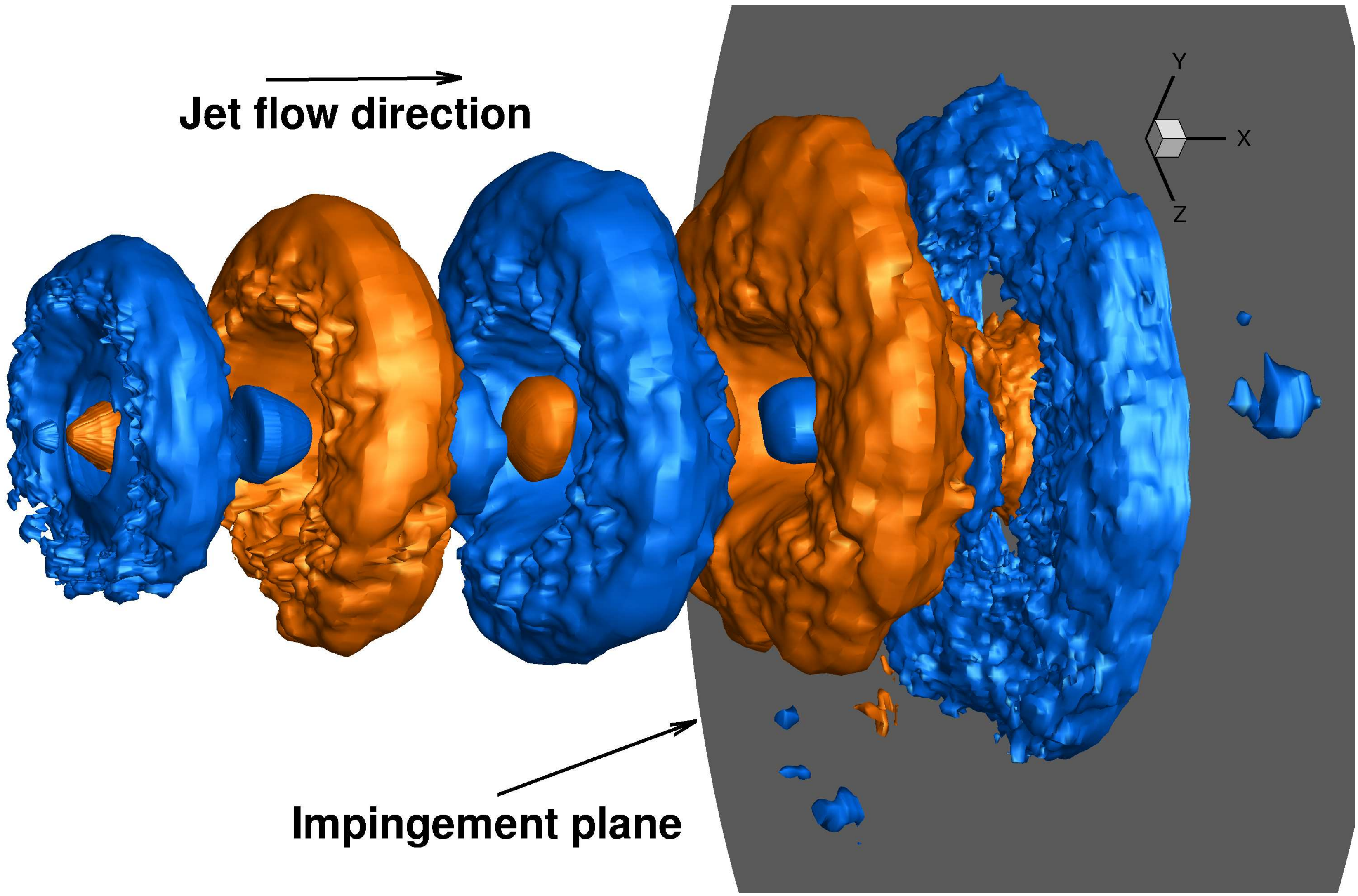
DMD Mode Norm versus Temporal Frequency



Coherent Structures Identified by DMD



Pressure Disturbance Iso-Surfaces Associated with Vortex Rings



Summary and Outlook

- **Good overall agreement between experiments and corresponding simulations**
- **Simulations provide a better understanding of pulsed micro-actuator operation and provide important details not observable from experiments**
- **Simulations and DMD analysis identify coherent structures responsible for intense tonal noise generation in supersonic impinging jets**
- **Upcoming work will focus on new micro-actuator simulations as well as numerical flow control experiments with micro-jet injection**