Velocity/multi-scalar measurements in turbulent co-axial jets

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Background and Motivation

- Scalar mixing in turbulent flows plays an important role in many applications, both industrial and environmental:
  - Heat transfer, combustion, environmental pollution dispersion, atmospheric & oceanic sciences

- However, most scalar mixing studies have focused on the mixing of a single scalar
  - There has comparatively been relatively little work on multi-scalar mixing

Background and Motivation (cont.)

- Nevertheless, there have been some studies of multi-scalar mixing:

	Experimental	Computational
Homogenous, Isotropic Turbulence	• Warhaft (1981) • Sirivat and Warhaft (1982) • Warhaft (1984)	• Juneja and Pope (1996) • Vrieling and Nieuwstadt (2003) • Viswanathan and Pope (2008)
Jets	• Tong and Warhaft (1995) • Cai et al. (2011) • Soltys and Crimaldi (2015) • Li et al. (2017)	• Rowinski and Pope (2013)
Channel Flow	• Costa-Patry and Mydlarski (2008)	• Oskouie et al. (2015)
Boundary Layers	• Sawford et al. (1985) • Davies et al. (2000)	
Mixing Layers		• Cha et al. (2006) • Sawford (2006) • Sawford and de Bruyn Kops (2008) • Meyer and Deb (2012)

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Objectives: short, medium and longer term

- To develop a measurement technique capable of simultaneously measuring of two scalars *and* velocity in turbulent flows at high temporal and spatial resolution

- To (experimentally) study the evolution of two distinct scalars (temperature and helium) in a turbulent coaxial jet
  - Inspired by the experiment of Cai et al., *J. Fluid Mech*. (2011)

- To provide data for the testing of mixing models with the aim of (hopefully) validating and/or further improving them for use in multi-scalar mixing applications, similar to what has been undertaken by Cai et al., J. *Fluid Mech*. (2011) and Rowinski and Pope, *Phys. Fluids* (2013)

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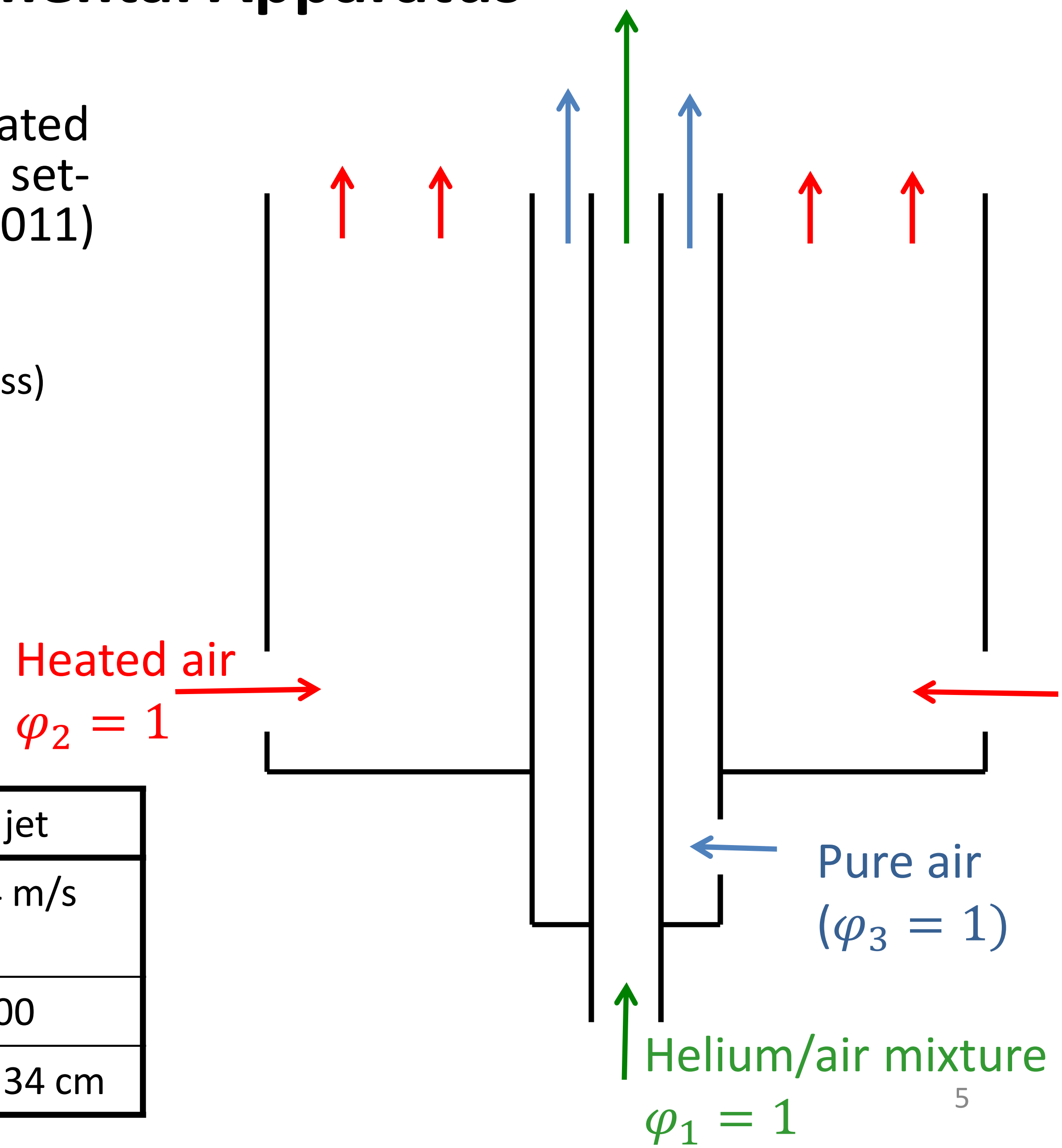
Experimental Apparatus

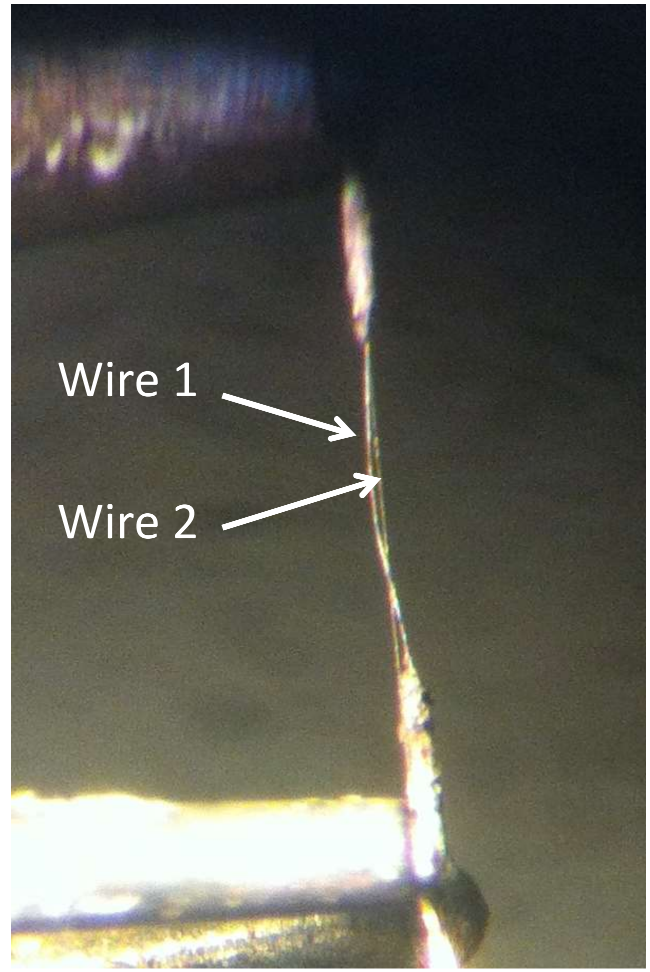
- Vertically oriented coaxial jet emanating into a co-flow of heated air (based on the experimental set-up of Cai *et al. J. Fluid Mech.,* 2011)
  - 1st (central) jet:
    - fully developed flow
    - mixture of helium (4% by mass) and air (96% by mass)
  - 2nd (annular) jet:
    - fully developed flow
    - pure (unheated) air
  - 3rd co-flow:
    - approximately uniform flow
    - heated air ($\Delta T = 6.0$ ℃)



	1st jet	2nd jet	3rd jet
U at jet exit	12.6 m/s	11.3 m/s	0.4 m/s
Re_{D_h}	3900	2300	3600
D_h	0.622 cm	0.318 cm	13.34 cm

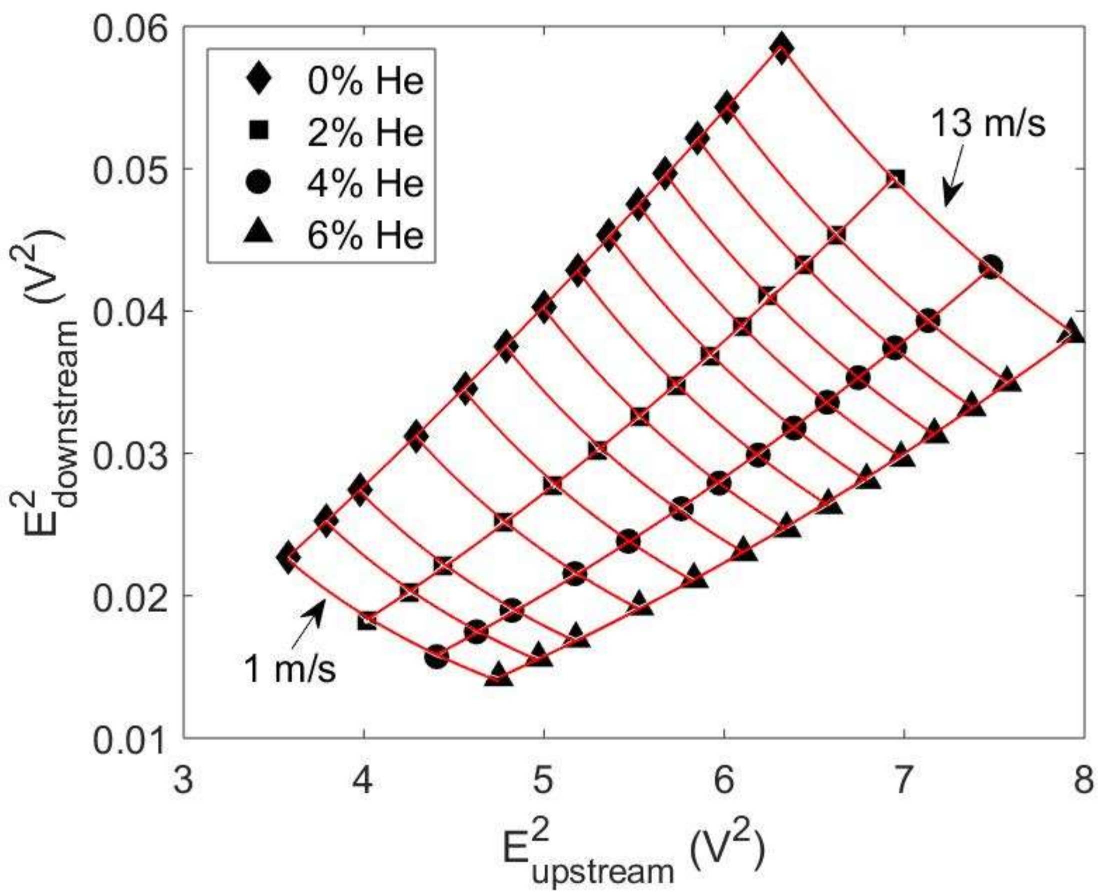
3-Wire Thermal Anemometry Probe for Simultaneous Measurements of U, C and T

- 3-wire probe consists of:
  - **Two** hot-wires to measure the velocity and concentration ("Interference" or "Way-Libby" probe)
    - Wires are placed close together (5-15 µm)
  - **One** cold wire (not shown) to measure the temperature (insensitive to velocity and concentration)



Interference probe to simultaneously measure velocity and concentration

Interference Probe for Isothermal Case



- Concentration determined from a function of both wire voltages:

$$C = f(E^2_{up}, E^2_{down})$$

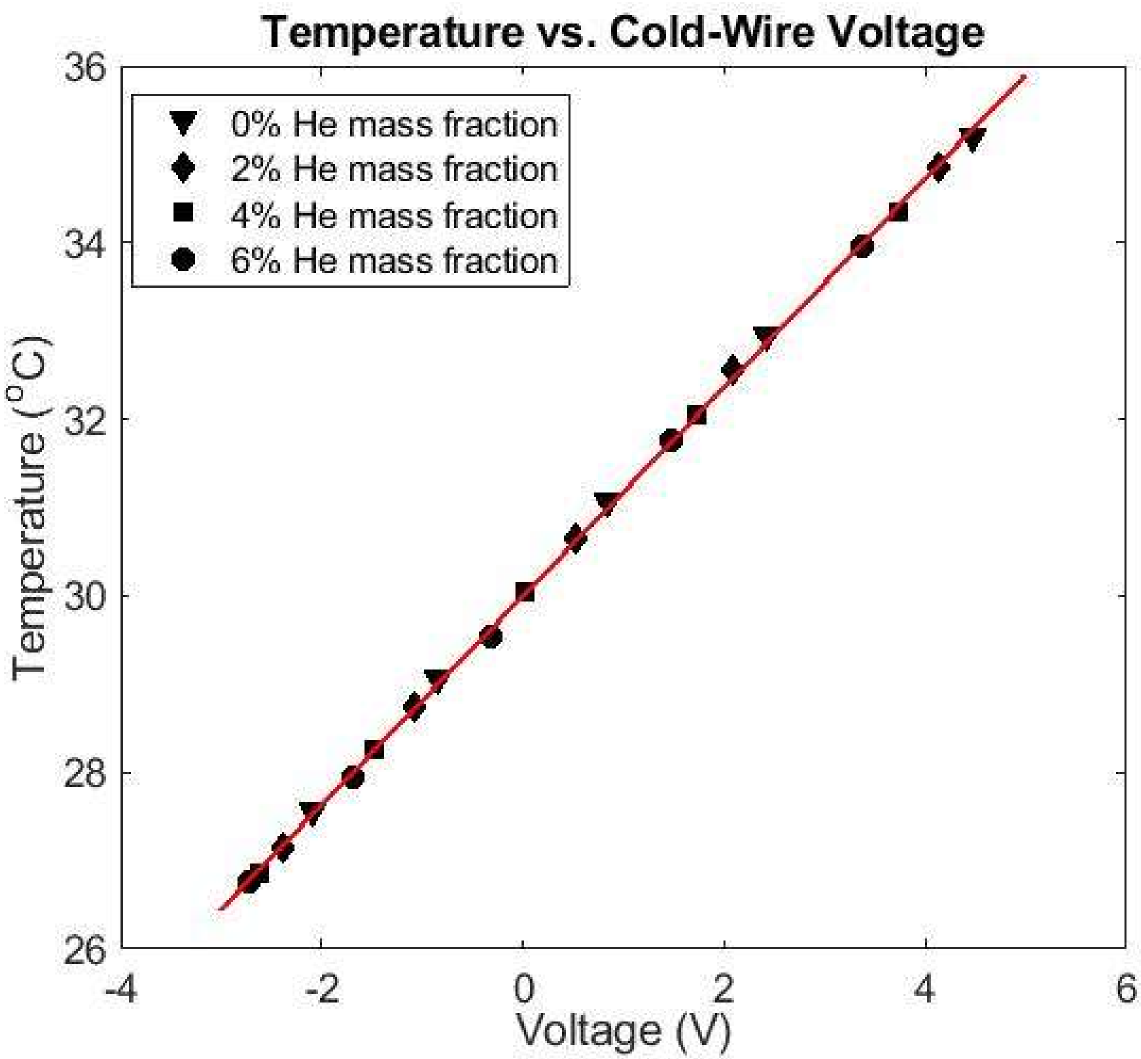
- Upstream wire follows King's Law:

$$U = \left[\frac{E^2_{up} - A(C)}{B(C)}\right]^{1/n}$$

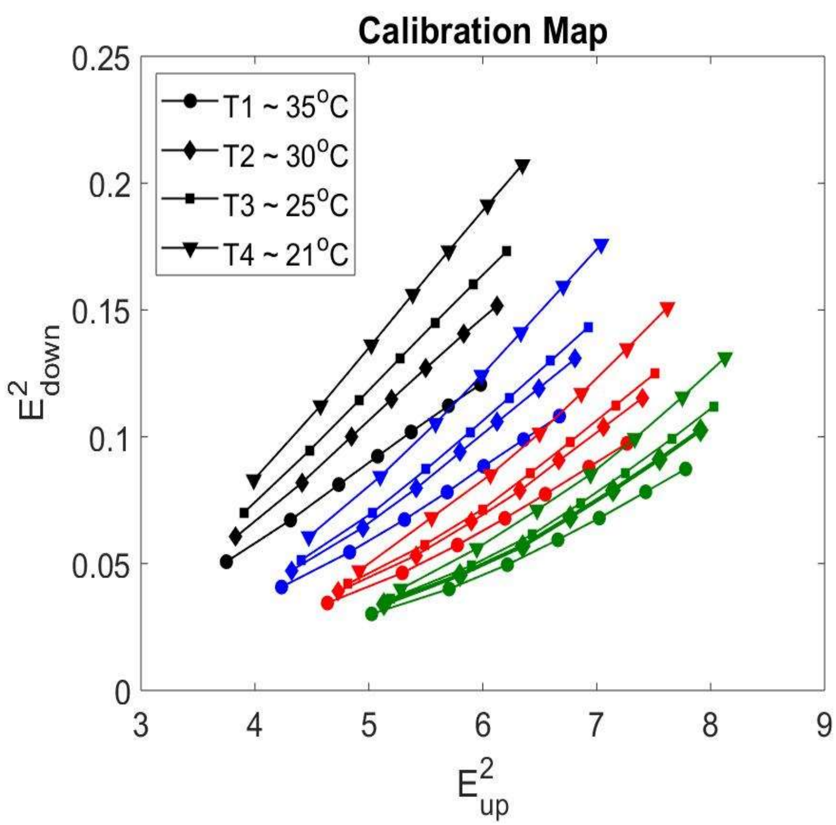
Cold-Wire Thermometer

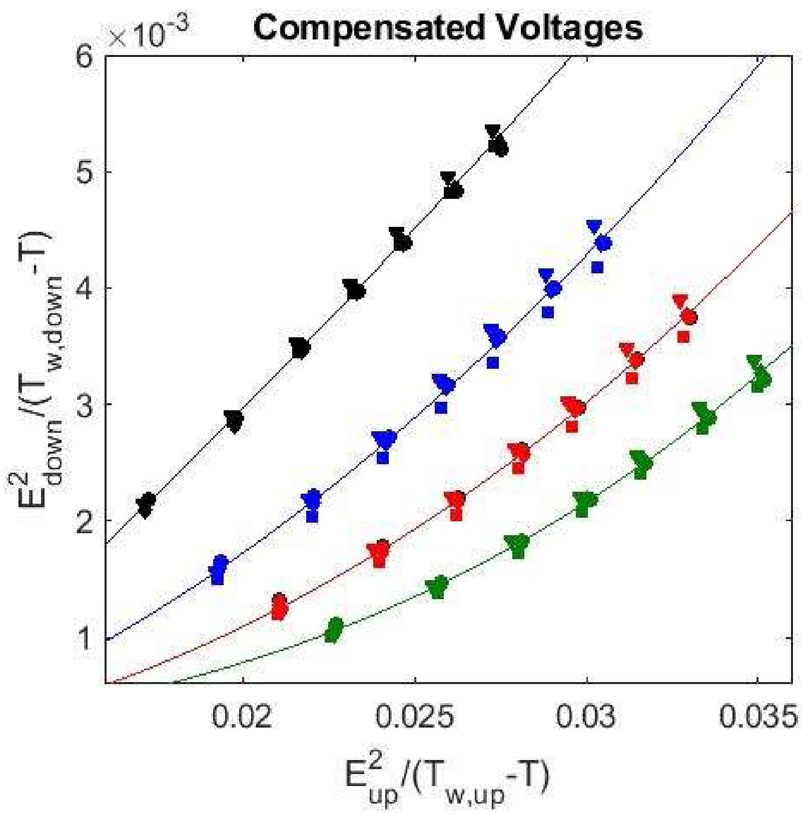
- Temperature is linearly related to the voltage drop across the sensor: $T = A_t + B_t V$

- Low sensitivity to the fluctuating velocity and He concentration



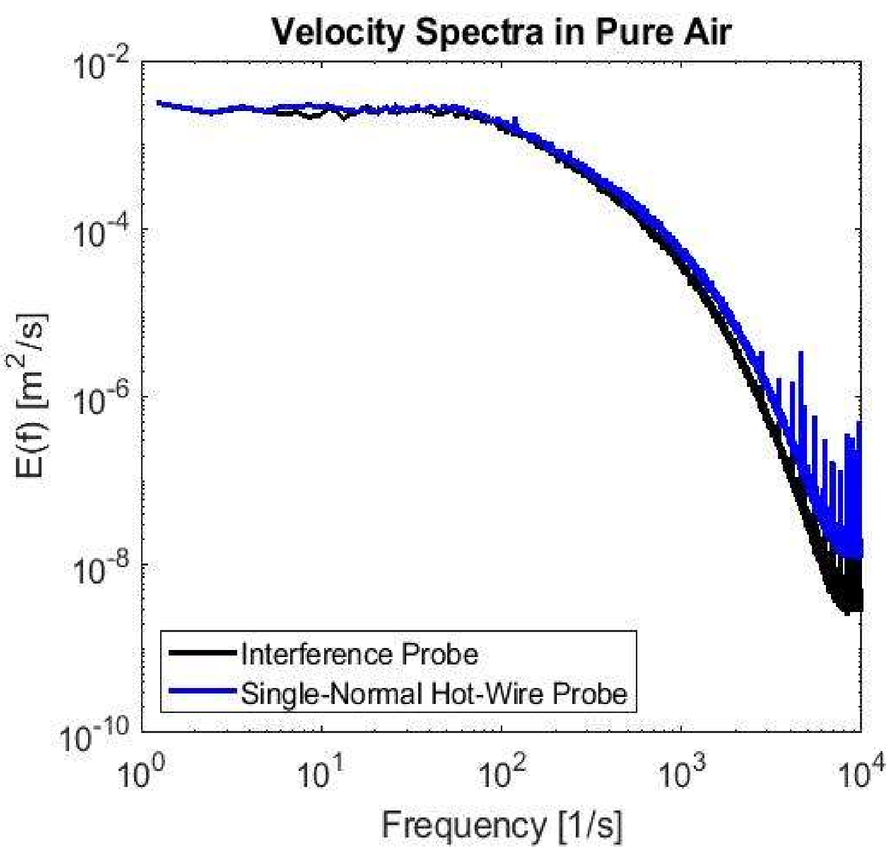
Interference Probe: Extension to Non-Isothermal Case

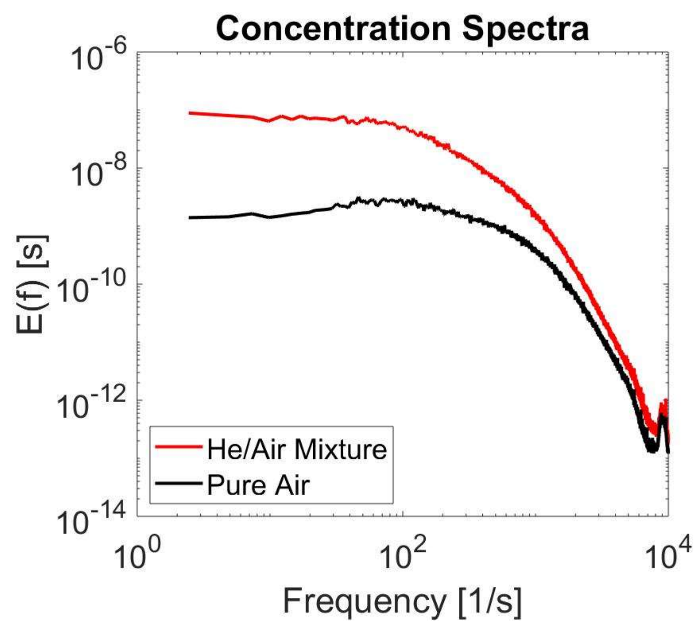


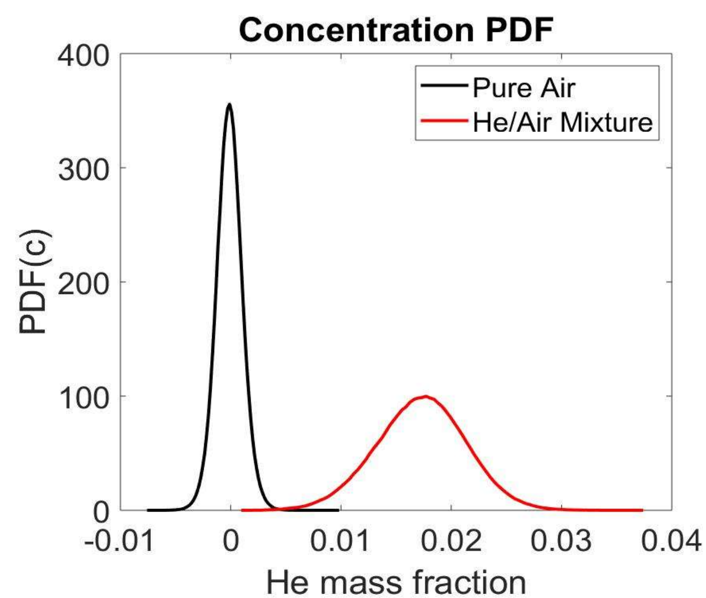


- Black: 0% He mass fraction
- Blue: 2% He mass fraction
- Red: 4% He mass fraction
- Green: 6% He mass fraction

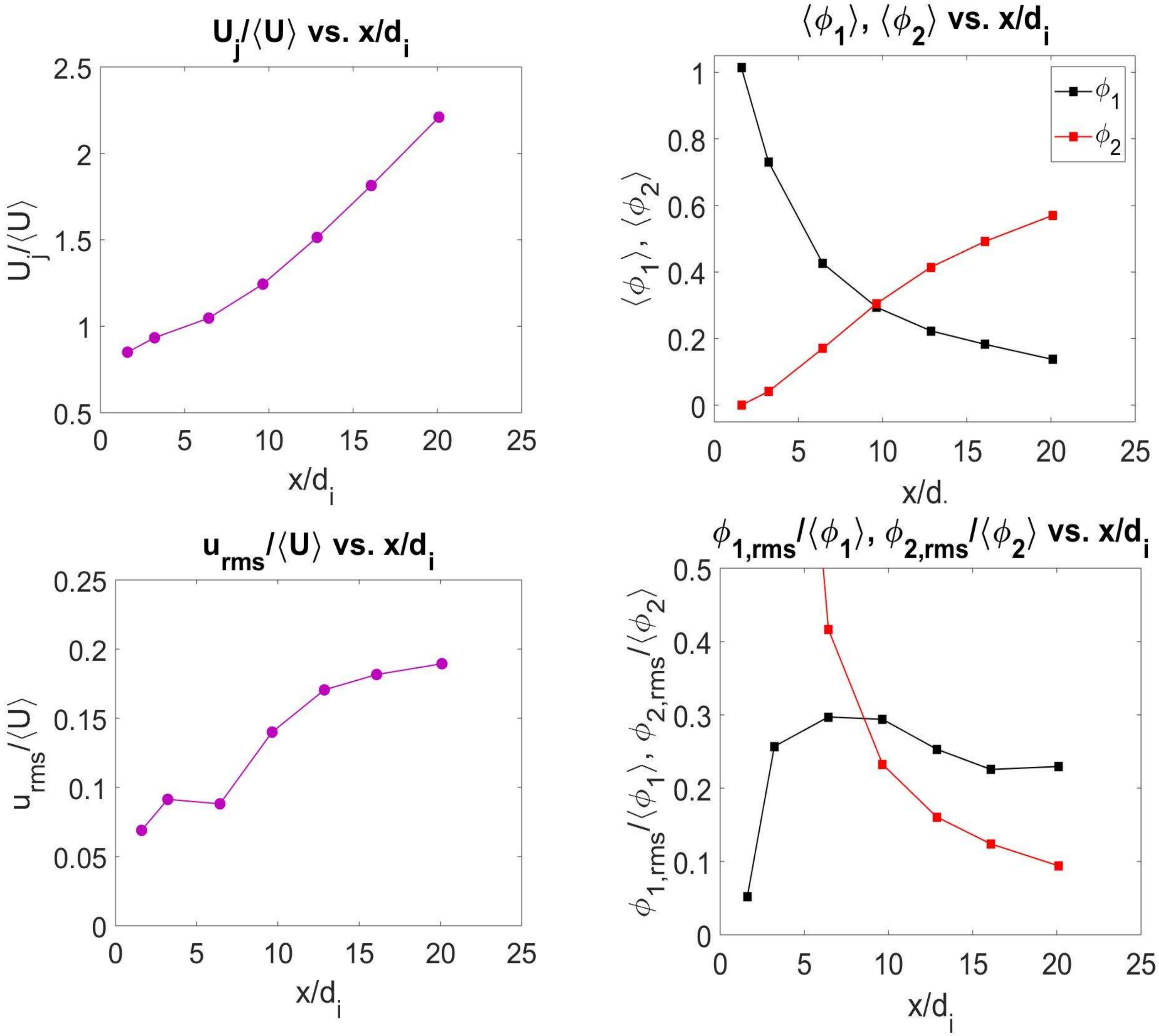
Validation of Interference Probe



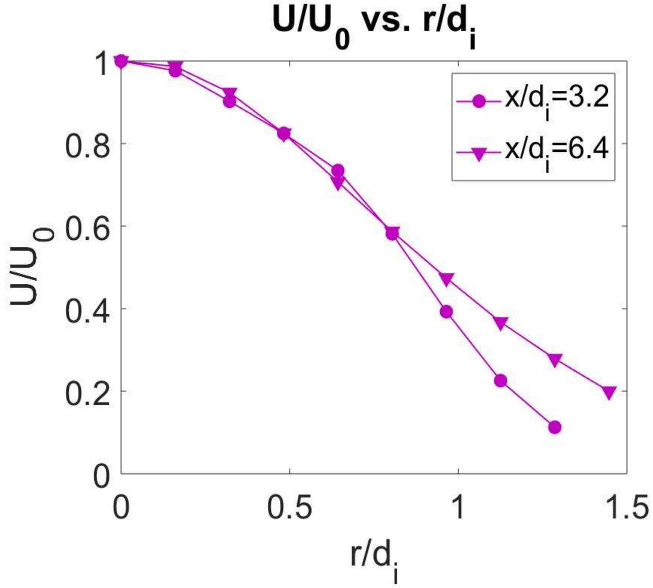


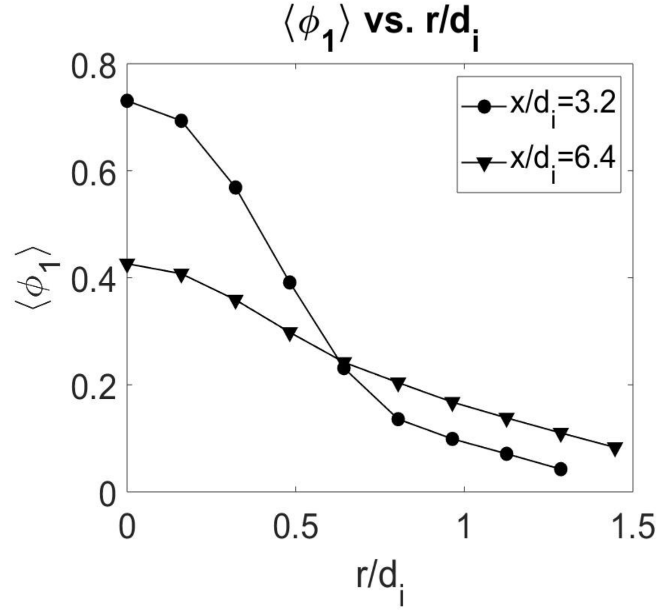


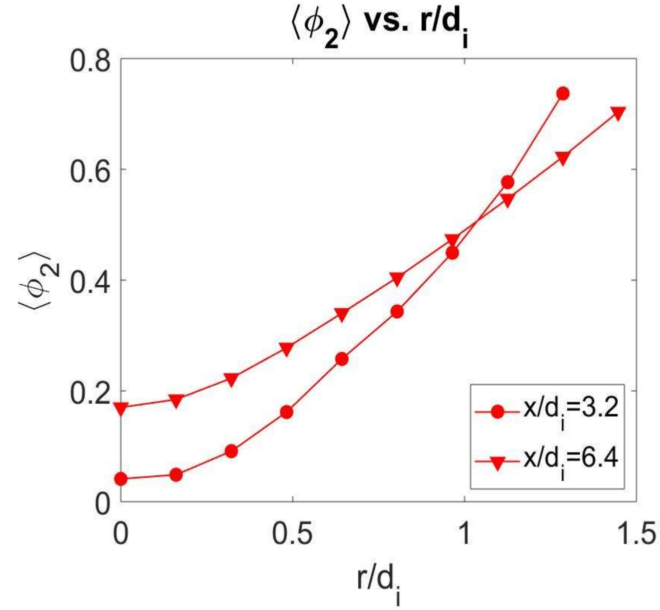
Results: Downstream Evolution of Centerline Statistics

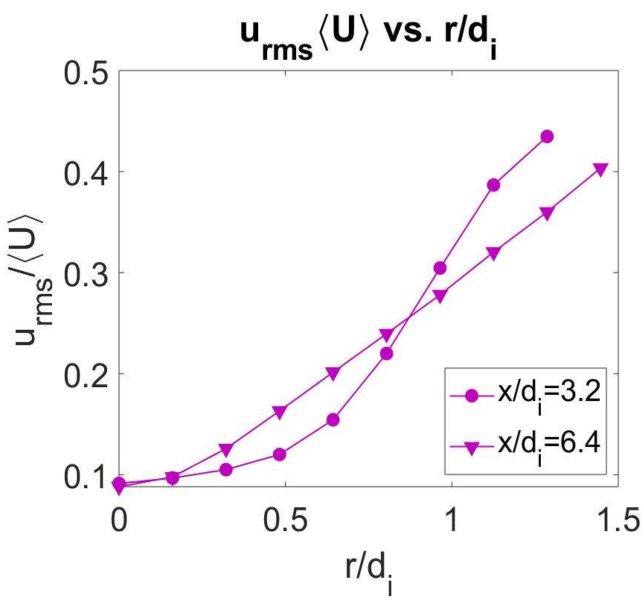


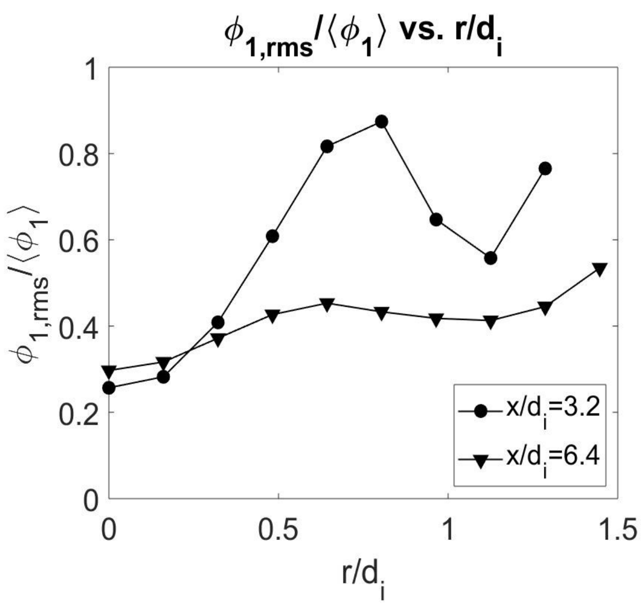
Results: Radial Profiles

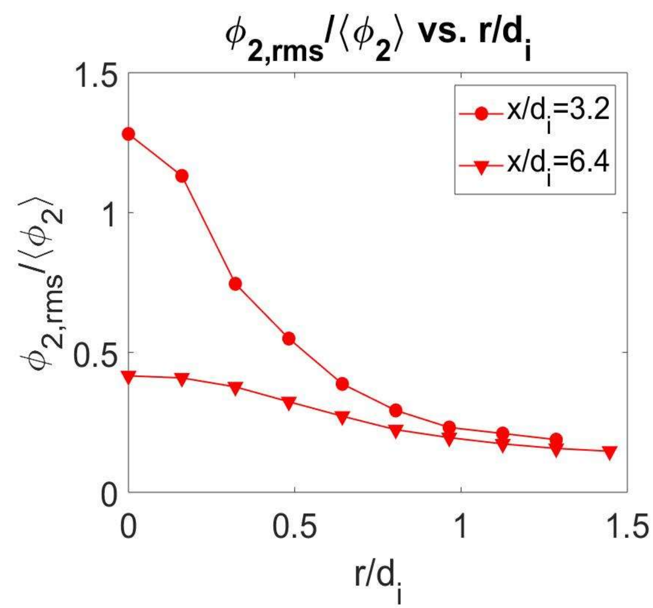




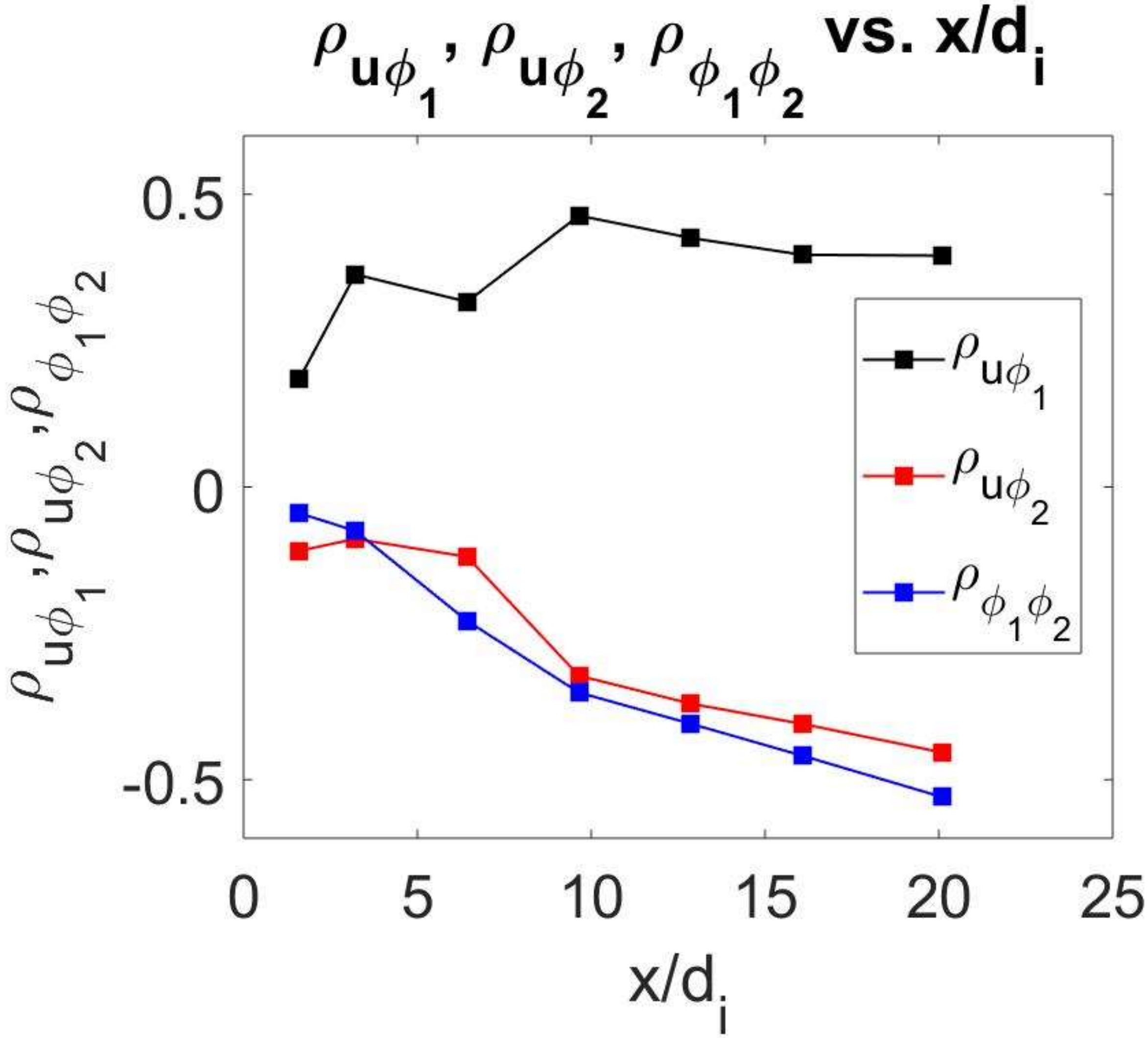




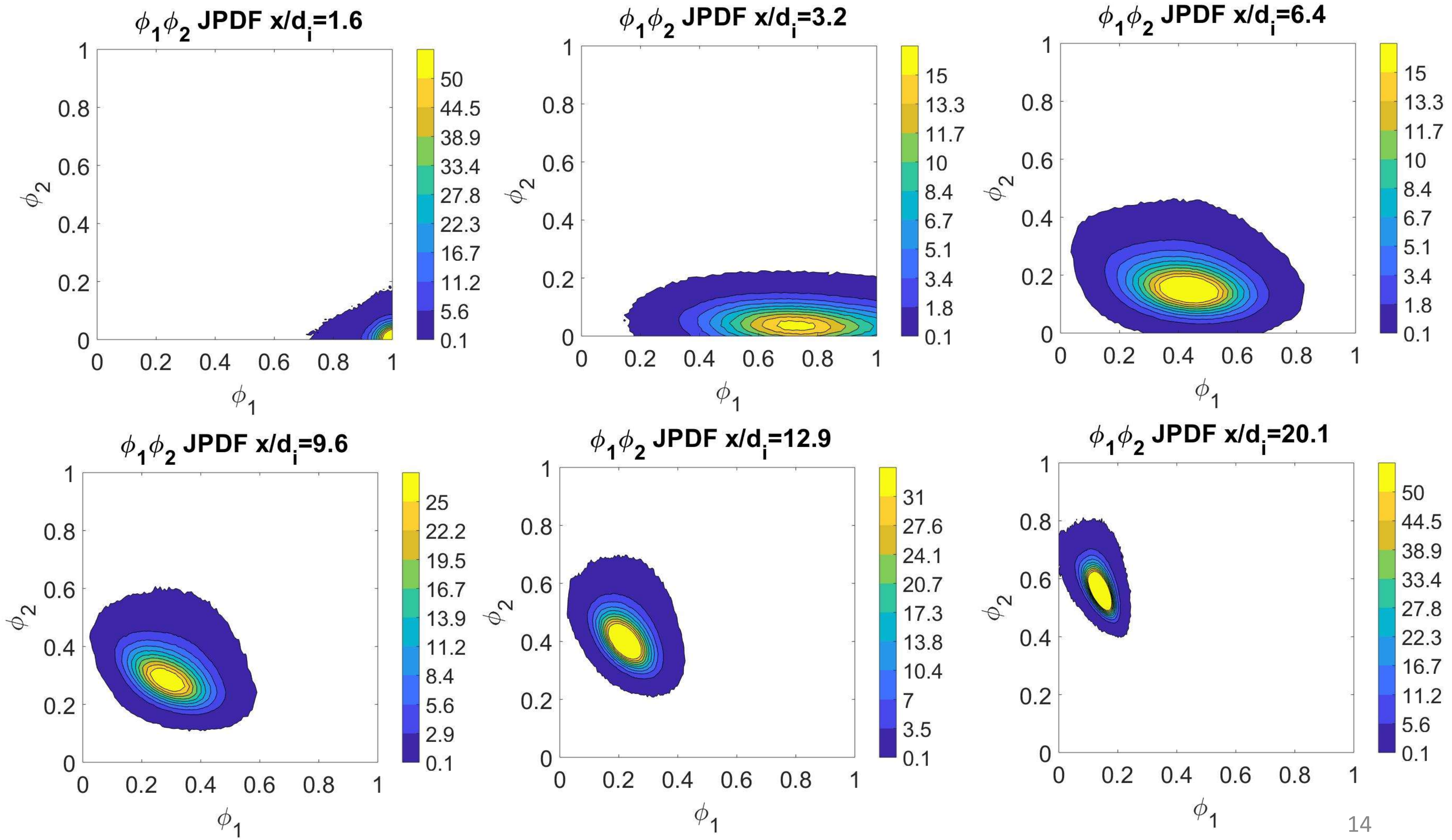




Results: Mixed Statistics → Correlation Coefficients



Results: Downstream Evolution of JPDFs of ϕ_1 and ϕ_2



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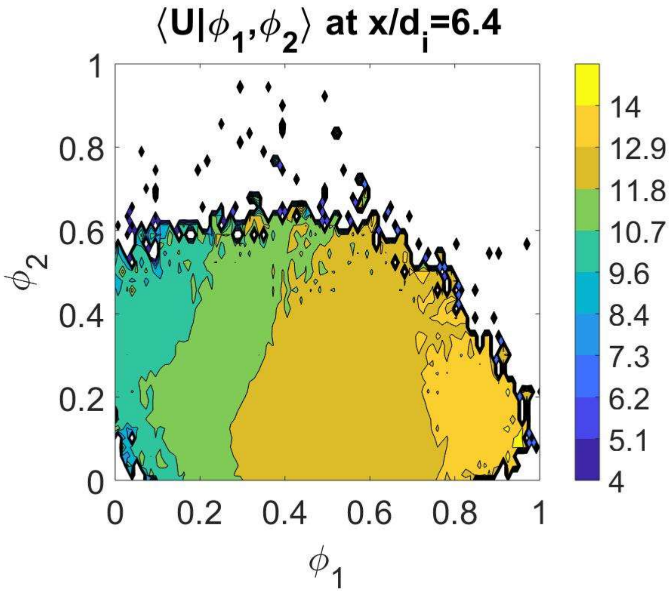
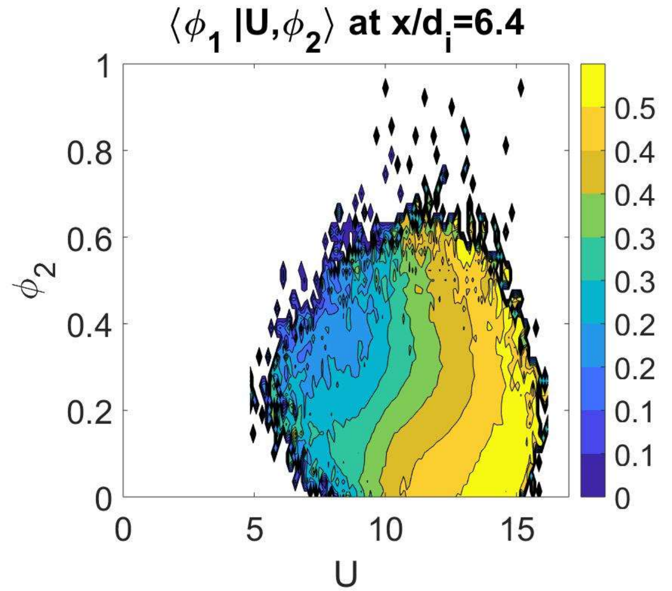
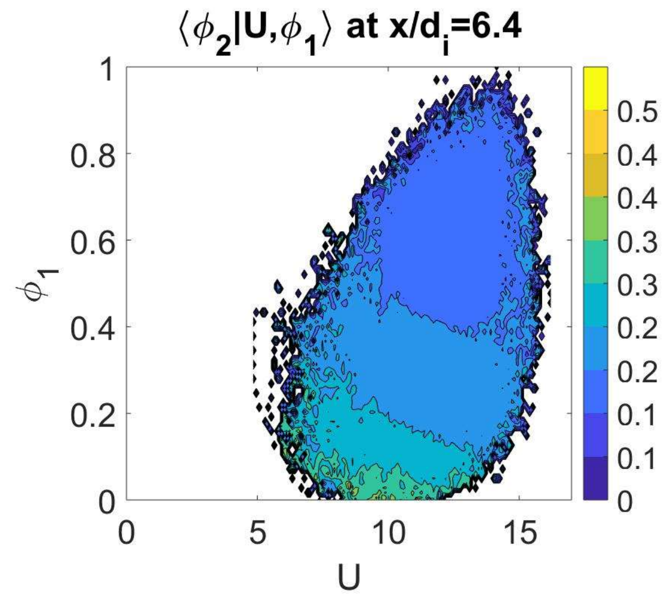
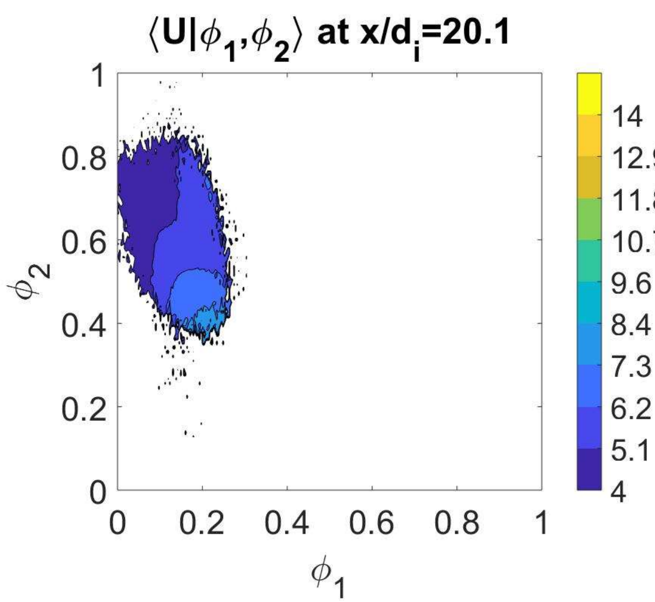
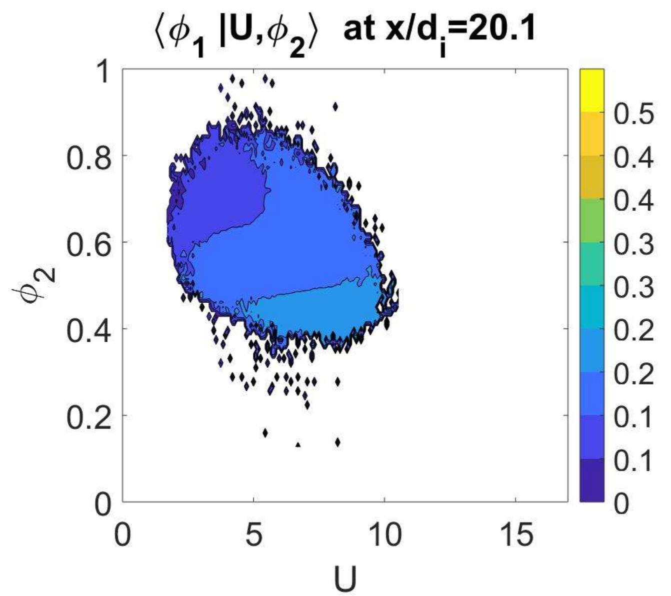
Results: Conditional Expectations

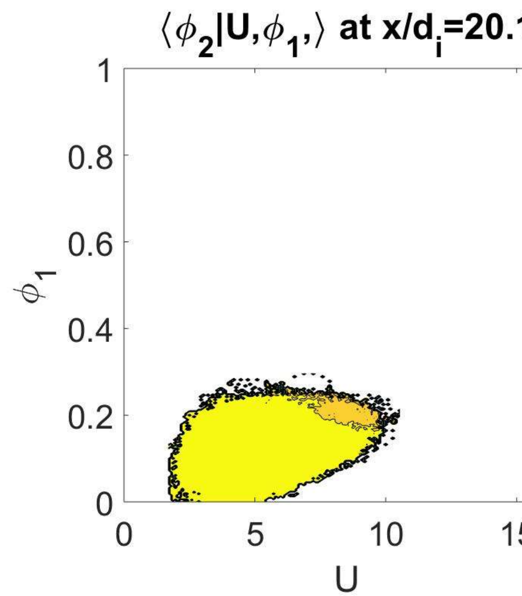












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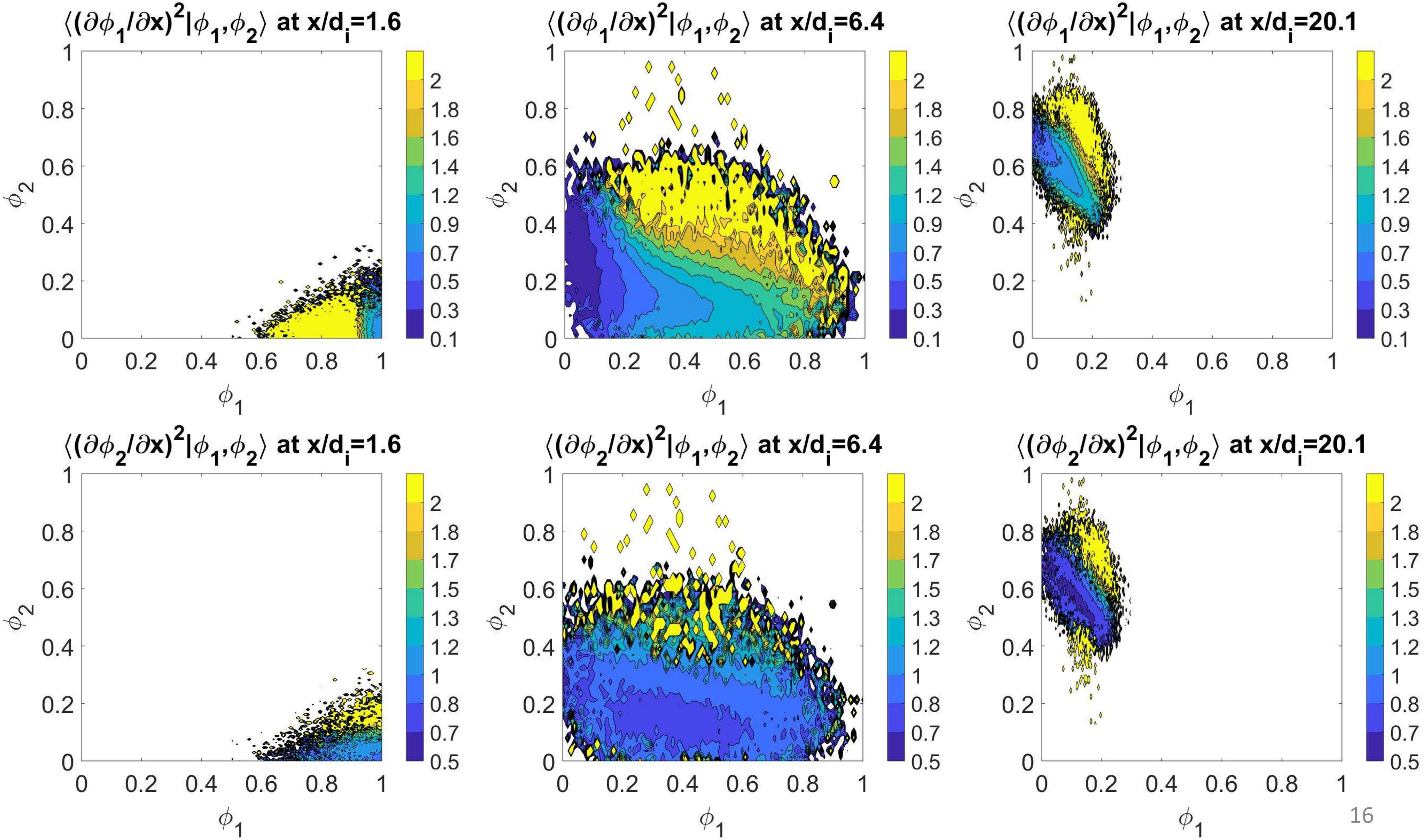
Results: Centerline Conditional Dissipations



Conclusions & Future Work

- Developed 3-wire, thermal-anemometry-based probe capable of simultaneously measuring 2 scalars *and* velocity in a turbulent flow
- Made measurements of velocity and 2 scalars in a coaxial jet with a co-flow
- Future work will involve:
  - Pursuing additional noise reduction techniques
  - Furthering the understanding both the physics and modelling of multi-scalar mixing by way of simultaneous U, C & T measurements

Questions?