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Observations of Similarity in Non-Evaporating Sprays

ILASS Americas 2021

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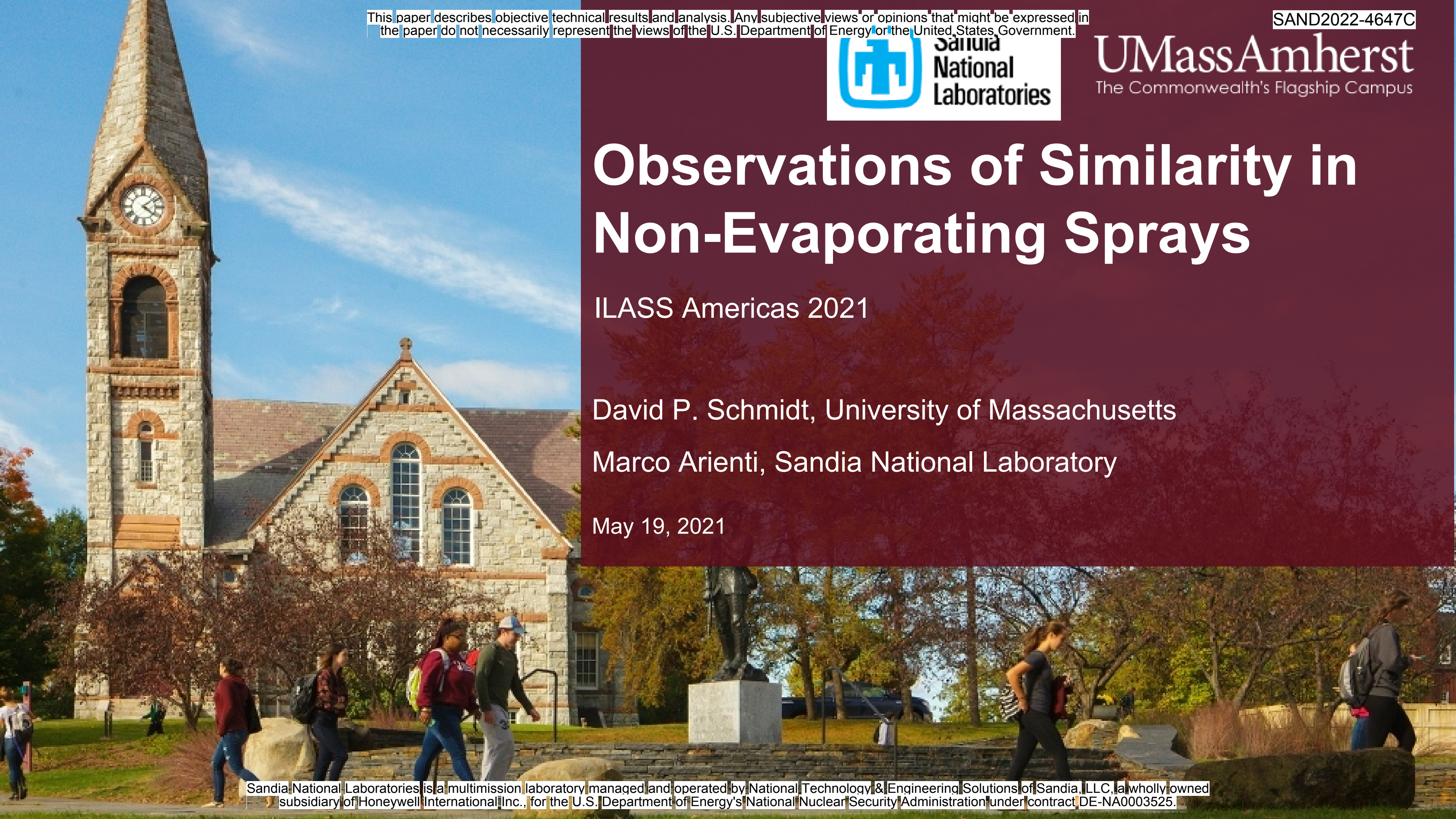

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Your Friendly, Yet Remote Authors:

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- Some aging may have occurred since these photos were taken. It couldn’t be helped.

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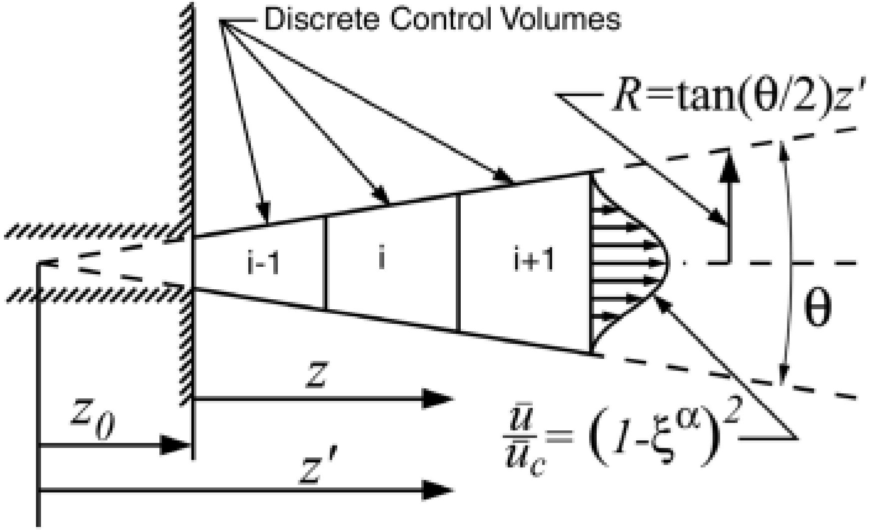
Overview

- Examination of a 1-D model reveals a mathematical surprise
- Comparison to DNS for reality check
- Plaintive whine for experimental data



From Musculus & Kattke, 2009

Motivation

- The yield of what you get/what it costs you is excellent
- Basic physics are much more accessible than CFD
- Basis for a CFD model (ELMO)

Homer Simpson image used with permission of the producer's nephew

Assumptions

- Liquid and gas share so much interfacial area, that they move at the same velocity
- Liquid volume fraction and velocity both share the same radial profile (unity Schmidt number)
- Constant densities
- Non-evaporating
- Constant spray angle

Equations for Mass and Momentum

- Overbars indicate time and radial average

$$\beta = \frac{1}{\bar{X}_f \bar{u}} \int X_f u dA$$

- Beta is a parameter representing the correlation of LVF and velocity

$$m_{f,i}^{t+1} = m_{f,i}^{t} + \rho_f \left[(\beta \bar{X}_f \bar{u} A)_{i-1}^{t} - (\beta \bar{X}_f \bar{u} A)_{i}^{t} \right] \Delta t \quad (11)$$

- Momentum should, strictly, have a triple correlation

$$M_i^{t+1} = M_i^t + \left[(\beta \bar{\rho} \bar{u}^2 A)_{i-1}^{t} - (\beta \bar{\rho} \bar{u}^2 A)_{i}^{t} \right] \Delta t \quad (12)$$

Surprising result

- Change variable to replace velocity with dimensionless *two-phase* momentum
- Take limit as time step and cell size go to zero
- Two-phase momentum is proven equal to LVF via similarity
- True for all times and axial distances

$$L^* \equiv \frac{\bar{\rho}\bar{u}}{\rho_l u_{inj}}$$

$$\boxed{\bar{X}_f = L^*}$$

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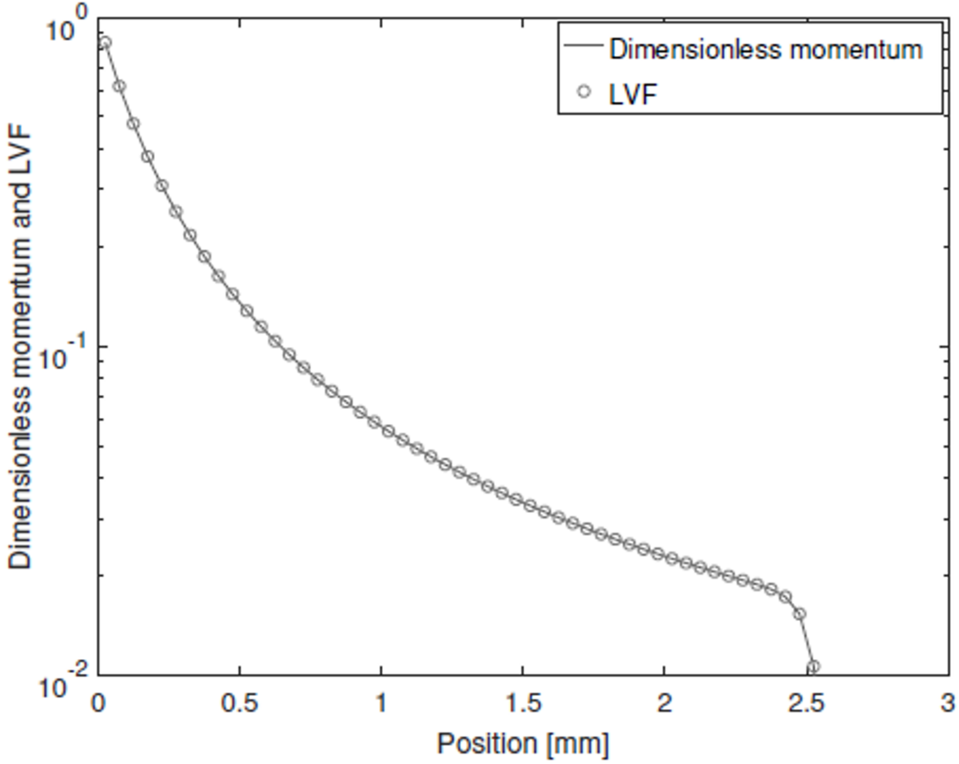
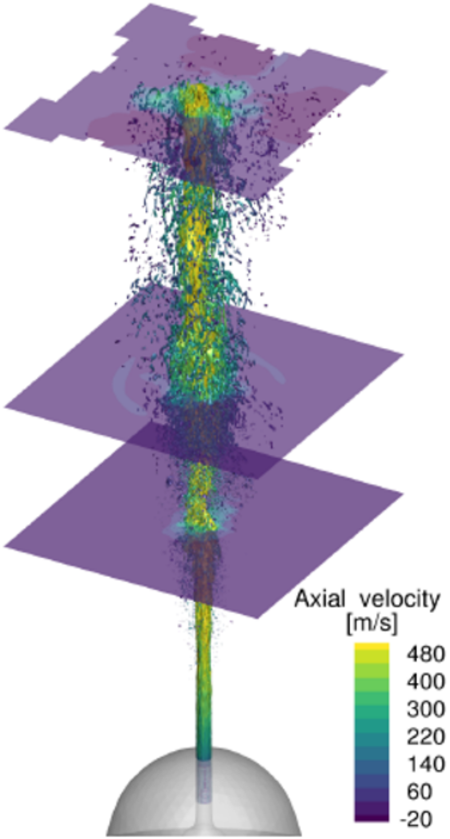
Verification

- Ran publically-available Musculus-Kattke code
- Snapshot at 0.01 ms ASOI



How do we validate this?

- Need both mass based diagnostics for LVF and velocity
- Not usually made for the same spray at the same location
- DNS is our only hope



The interface-capturing code CSLVOF

In collaboration with FSU and the LBNL AMReX co-design center

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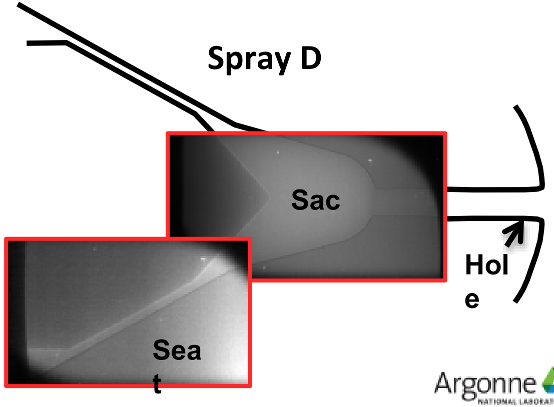
- Sharp-interface discretization of multi-phase Navier-Stokes eqns. with Moment of Fluid interface representation [1].
  - ✓Fully compressible formulation [2]
  - ✓Non-conformal moving wall boundaries
  - ✓Adaptive Mesh Refinement (AMReX)
  - ✓Large Eddy Simulation (WALE)
  - ✓ Cavitation [3] and surface evaporation [4]

- Injector surfaces are reconstructed from X ray radiography and converted into level set representation



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[1] Jemison, et al., J. Sci. Comput. 54(2-3) (2013) 454-491.

[2] Jemison, Sussman, Arienti, J. Comput. Phys., 279, (2014) 182-217.

[3] Arienti et al., Proceedings of the Combustion Institute 2021.

[4] Wenzel and Arienti, Proceedings of the 31st ILASS-Americas, May 2021.

Validation case: Spray D, served cold

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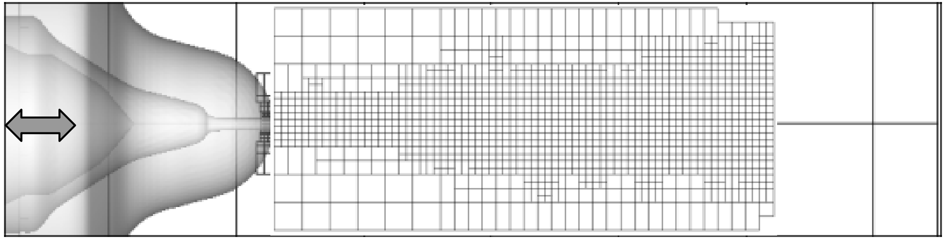
3D domain (3.6 x 3.6 x 15.6 mm) with AMR, Δx min = 2.5 µm

pressure b.c.
$P = p_{inj}$



pressure b.c.
$P = p_a$

Geometry	Nominal
Nozzle Outlet Diameter	186 µm
Nozzle K-Factor	1.5
Nozzle L/D	---

SCC Cold Conditions	
Fuel	n-dodecane
Injection Pressure	1000 bar
Fuel Temperature	300 K
Ambient Temperature	300 K
Ambient Density	22.8 kg/m^3

External flow (from simulation)	
Mass flow rate	10.2 ± 0.4 g/s
Momentum flow rate	5.06 ± 0.3 N
Cv	0.967 ± 0.026
Cd	0.946 ± 0.036

Computed Profiles

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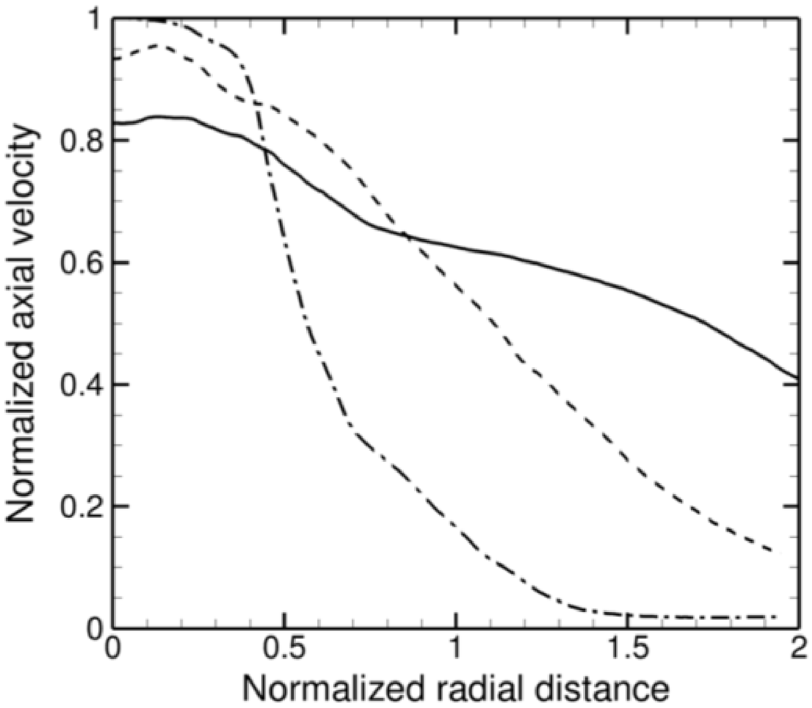
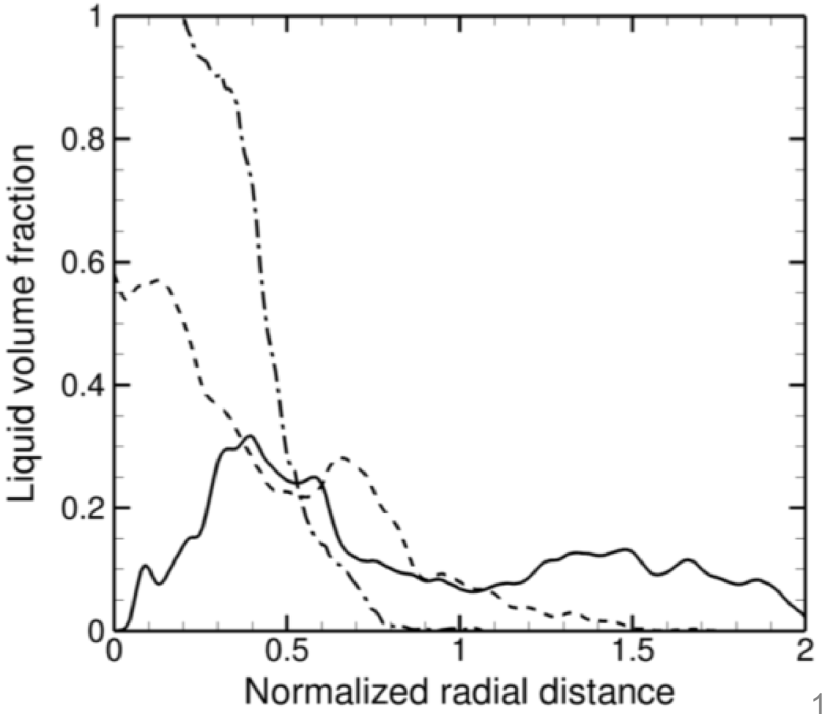
- Time averaged profiles at 7.8, 19, and 58 diameters downstream

Axial w/w_{MAX}

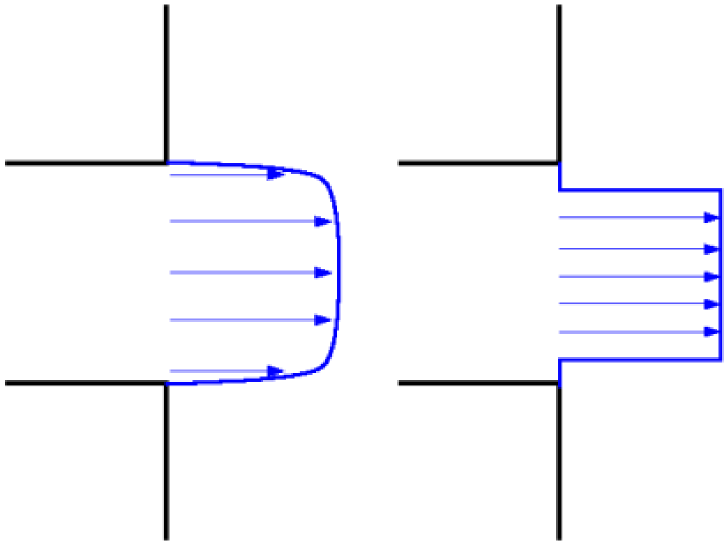


Liquid volume fraction

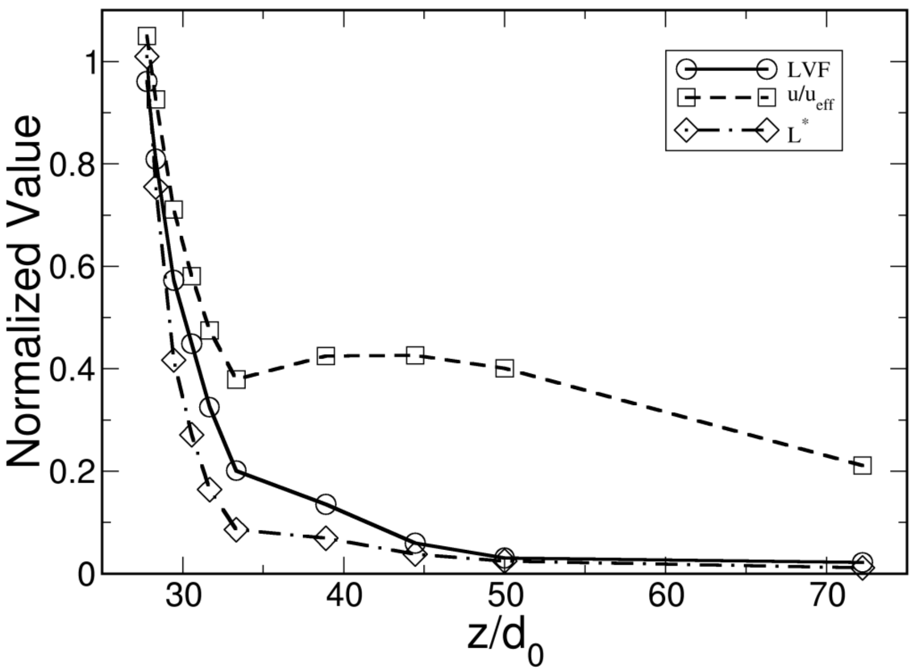


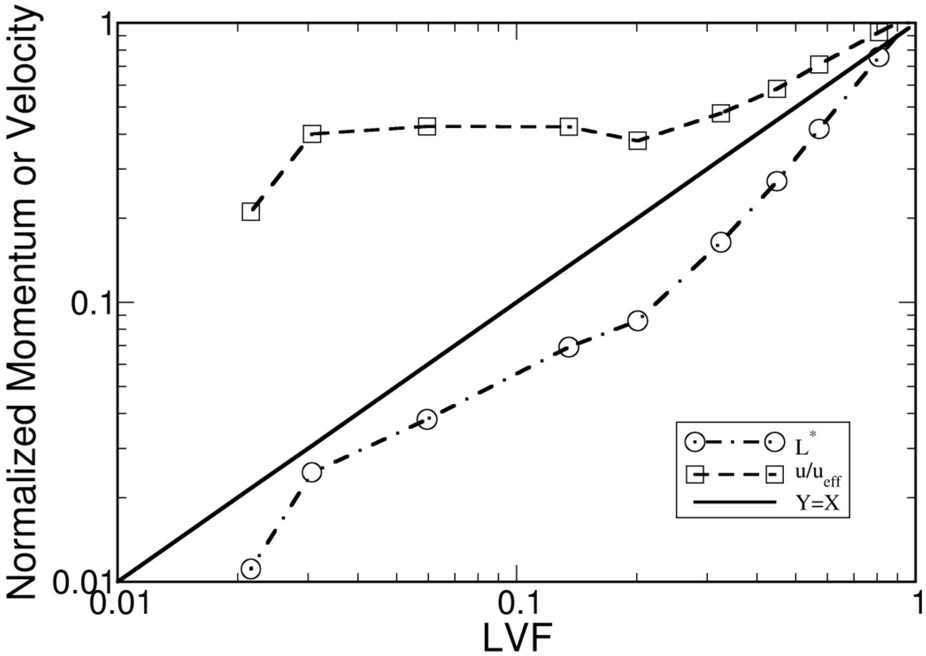
Caveats

- For extracting from DNS, assume half angle of 5.2 degrees
  - Velocity profiles are wider than LVF
- Analysis requires a single uniform orifice exit velocity
  - Use Ca, Cv
- Time averaging is over a relatively short time



Do the Analysis and DNS Agree?





- Transverse integrated, time-averaged results

Conclusions

- Analysis of a 1-D model indicates that two-phase momentum (not just liquid) is similar to LVF
- DNS simulations are supportive, but not conclusive

Future work

- Longer time-averaging
- Investigate transverse profile shapes
- Compare with Kastengren et al.'s assertion that mass-averaged velocity is proportional to transverse integrated mass
- Formalize details of transverse integration area

Acknowledgements

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Questions?

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