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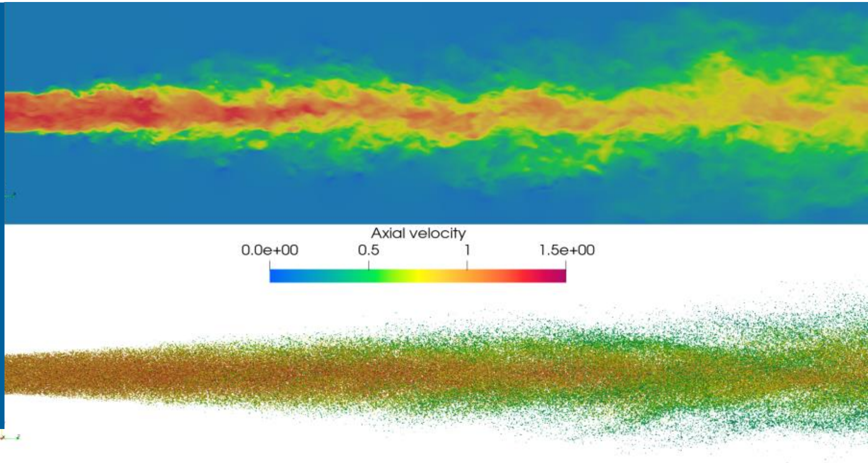
LARGE EDDY SIMULATION OF PARTICLE-LADEN FLOWS USING SPECTRAL ELEMENT METHOD



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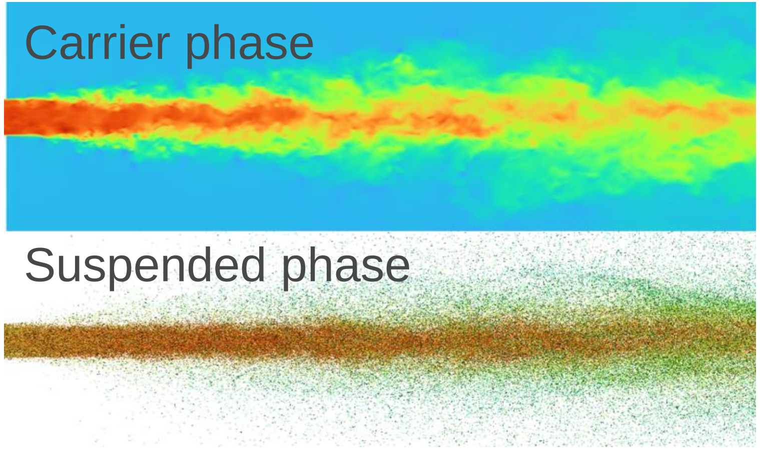
OUTLINE

- Introduction
- Numerical method
- Computational setup
- Single-phase jet
- Particle-laden jet
  - **Effect of particle collisions**
  - **Effect of injection parameters**
  - Effect of sub-cycling, grid refinement, hydrodynamic forces, particle distribution
- Conclusions

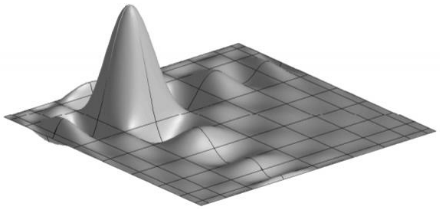
INTRODUCTION

- Turbulent particle-laden jet applications:
  - Gas-turbine engines, fluidized bed, flame spray pyrolysis, among others.
- Modeling approaches:
  - Eulerian-Eulerian (EE)
  - Eulerian-Lagrangian (EL)
- Levels of fidelity:
  - Reynolds-Averaged Navier-Stokes (RANS)
  - Large eddy simulation (LES)
  - Direct numerical simulation (DNS)/ Particle-resolved (PR) DNS
- Objective of this work:
  - Conduct high-fidelity **LES** of turbulent particle-laden jet flows using spectral-element method (**SEM**) in an **EL framework**.



NUMERICAL METHOD

- Spectral element method (SEM) (Patera, 1984; Maday & Patera, 1989) implemented in the Nek5000 code.
  - Weak formulation (Continuous-Galerkin)
  - N^{th} order tensor-product Lagrange polynomials at GLL points.
    $G = E(N+1)^d$, G: grid points, E: elements
  - Exponential convergence with N → High accuracy at low cost.
  - Very low numerical dissipation and dispersion.
  - Low-Mach formulation for compressible flows.
  - Characteristics-based time integration → CFL ~ 2.0



2D basis function, N=10

$$u_N(x) = \sum_{k=0}^{N} u_k h_k(x)$$

- Lagrangian stochastic parcels approach was used.
  - Particle ODEs are solved using RK3-SSP → ppiclF library. (Zwick, 2019)
  - Spectral interpolation of gas phase solution is done at parcel locations.
  - Particle properties and source terms are projected on the Eulerian grid via a Gaussian projection filter.

FLUID/PARTICLE COUPLING

$$\theta_l = 1 - \theta_g = \sum_{n=1}^{N_p} N_{d,n} \mathcal{V} G(|\boldsymbol{X_n} - \boldsymbol{x}|)$$

Gas phase – Navier-Stokes

Continuity: $\frac{D\rho_g}{Dt} = S_m \rightarrow \nabla \cdot u = -\frac{1}{\rho_g}\frac{D\rho_g}{Dt} - \frac{1}{\theta_g}\frac{D\theta_g}{Dt}$

Momentum:

$$\frac{D\boldsymbol{u}}{Dt} = -\frac{1}{\rho_g}\nabla p + \nu_g \nabla^2 \boldsymbol{u} + \frac{1}{\rho_g}\boldsymbol{S_u}$$

Heat:

$$\rho_g c_p \frac{DT}{Dt} = \nabla \cdot (k\nabla T) + \sum_{i=1}^{N_{spec}} [h_{i,in}(T_d) - h_{i,s}(T)] S_{m,i} + S_T$$

Mass:

$$\rho \frac{DY_i}{Dt} = -\nabla \cdot \boldsymbol{J}_i + S_{m,i}$$

Interpolation

Projection

Particle dynamics

$$\frac{D\boldsymbol{X_d}}{Dt} = \boldsymbol{V_d}$$

$$\frac{D\boldsymbol{V_d}}{Dt} = \boldsymbol{g} + \frac{1}{m_d}\boldsymbol{F_d}(\boldsymbol{u_d})$$

$$\frac{DT_d}{Dt} = \frac{1}{c_l m_d}\left[\dot{q}(T_d) + \frac{Dm_d}{Dt} h_L\right]$$

$$\frac{Dm_{i,d}}{Dt} = -\pi d_d \rho_g D B_d Sh_d = -\dot{m}_i(Y_{i,d})$$

$$\boldsymbol{S_u}(\boldsymbol{x}) = \frac{1}{\theta_g}\sum_{n=1}^{N_p} -N_{d,n}\boldsymbol{F}_{d,n} G(|\boldsymbol{X_n} - \boldsymbol{x}|); \quad S_T(x) = \frac{1}{\theta_g}\sum_{n=1}^{N_p} -N_{d,n}\dot{q}_n G(|\boldsymbol{X_n} - \boldsymbol{x}|); \quad S_m(x) = \frac{1}{\theta_g}\sum_{n=1}^{N_p} N_{d,n}\dot{m}_n G(|\boldsymbol{X_n} - \boldsymbol{x}|)$$

N_p: number of parcels; N_d: number of droplets per parcel; θ_g: Void fraction

$$G(\mathbf{r}) = \left(\sqrt{\pi\delta_f^2/4\ln 2}\right)^{-3} \exp\left[\frac{-|\mathbf{r}|^2}{\delta_f^2/4\ln 2}\right]$$

Formulation from: Ling, Balachandar & Parmar (2016); Capecelatro & Desjardins (2013)

COMPUTATIONAL SETUP

Mostafa et al. (1989)

Parameter	Value
Gas	**Air**
Density	1.178 kg/m^3
Mass flow rate	0.0021 kg/s
Jet diameter, D_J	25.3 cm
Reynolds No.	5712
Bulk velocity, U_B	3.54 m/s
Particles	**Glass**
Density	2500 kg/m^3
Diameter	105 μm
Mass loading ratio, L	0.2, 1.0
Stokes No.	~11.6

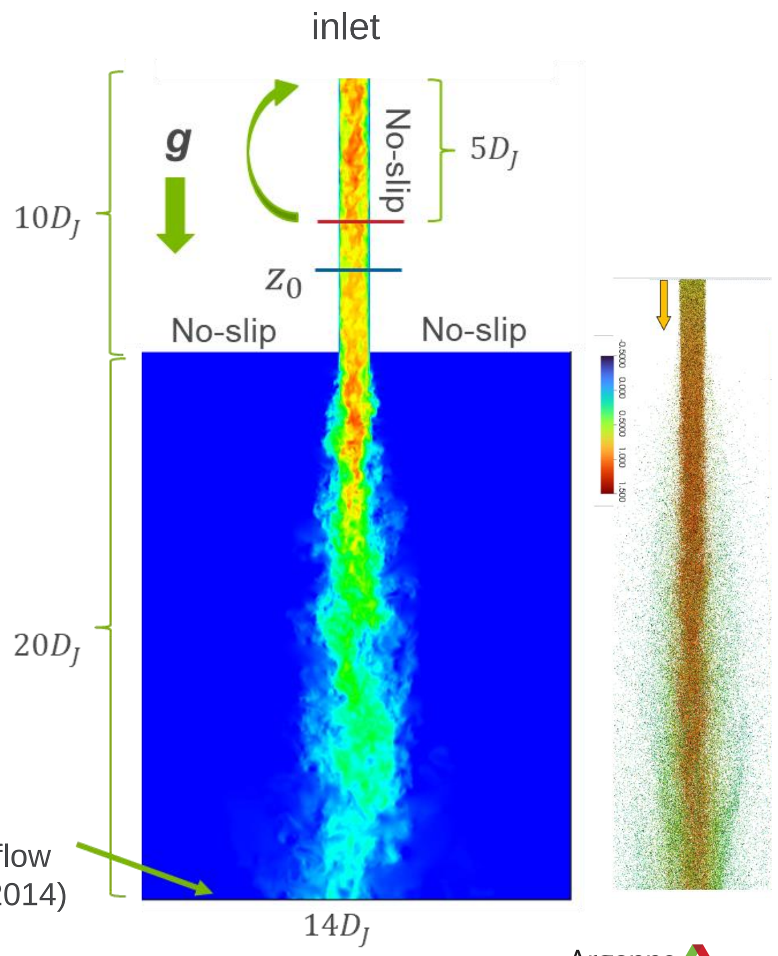
$$L = \dot{m}_p / \dot{m}_g$$

- Initial particle velocity $V_0/U_B = 0.5, 0.7, 0.9$

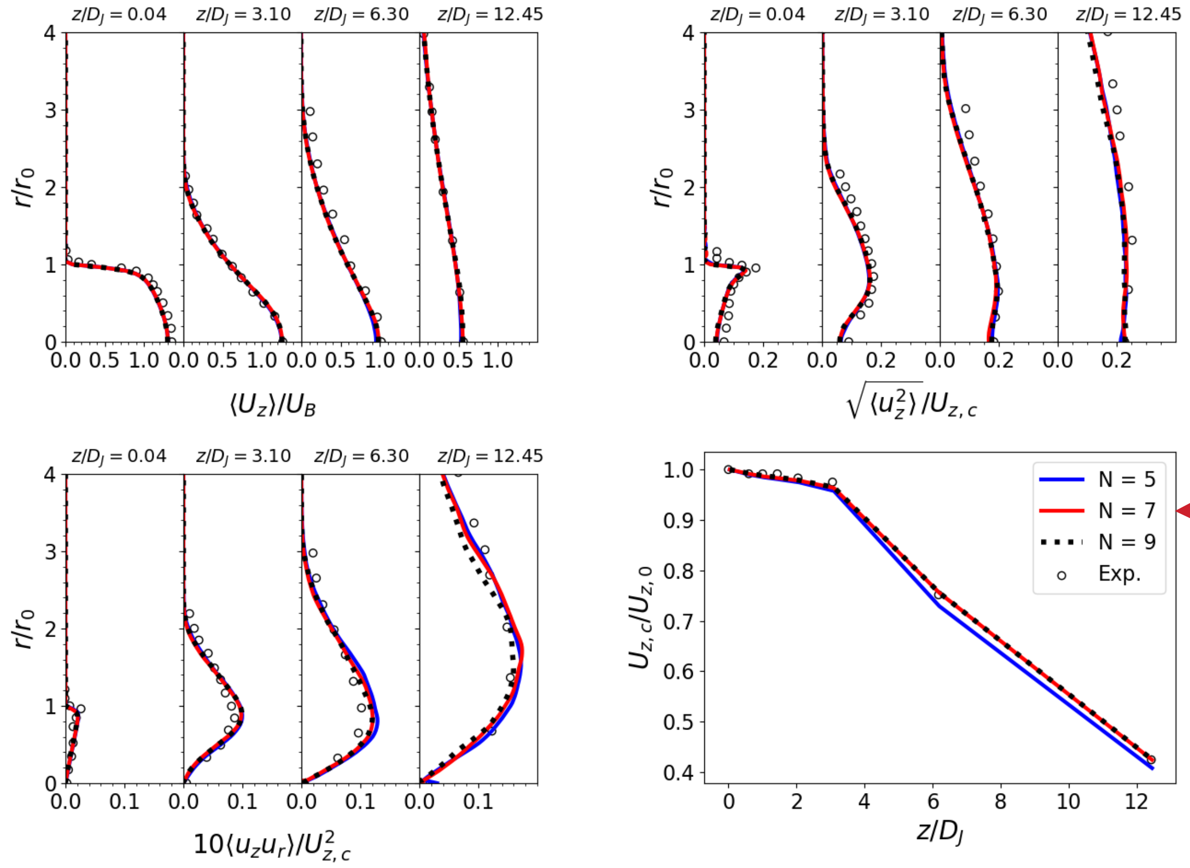
- Injection location $z_0/D_J = -5.0, -3.7, -2.0$

- Realistic particle distribution based on experimental profiles

- $E = 75k$ elements
- $N = 7$
- $G = 25.8\ M$
- $\frac{\Delta x_c}{D_j} = 0.0085 - 0.0471$

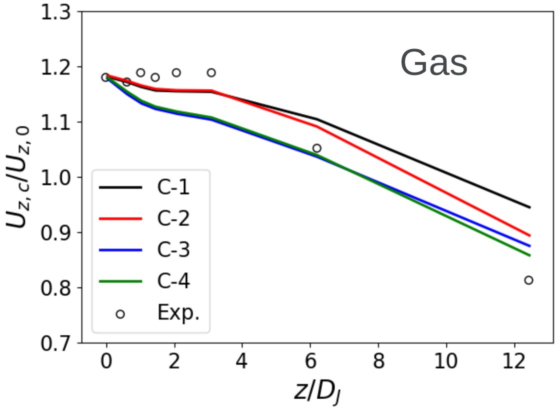


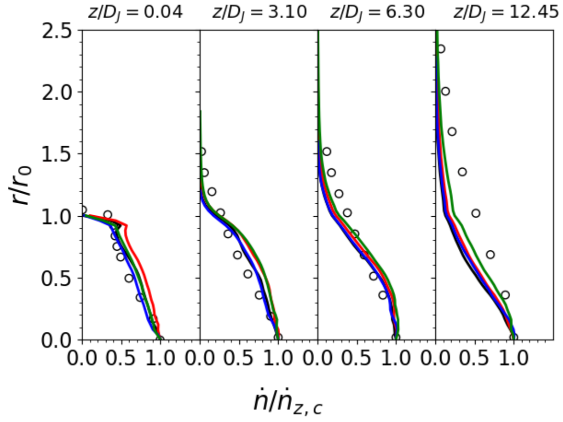
SINGLE-PHASE JET

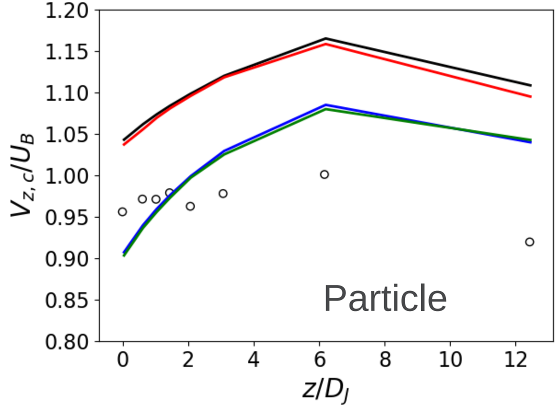


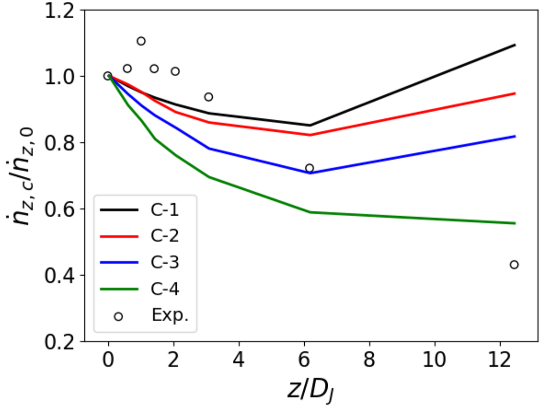
Grid convergence

PARTICLE-LADEN JET: P-P COLLISIONS







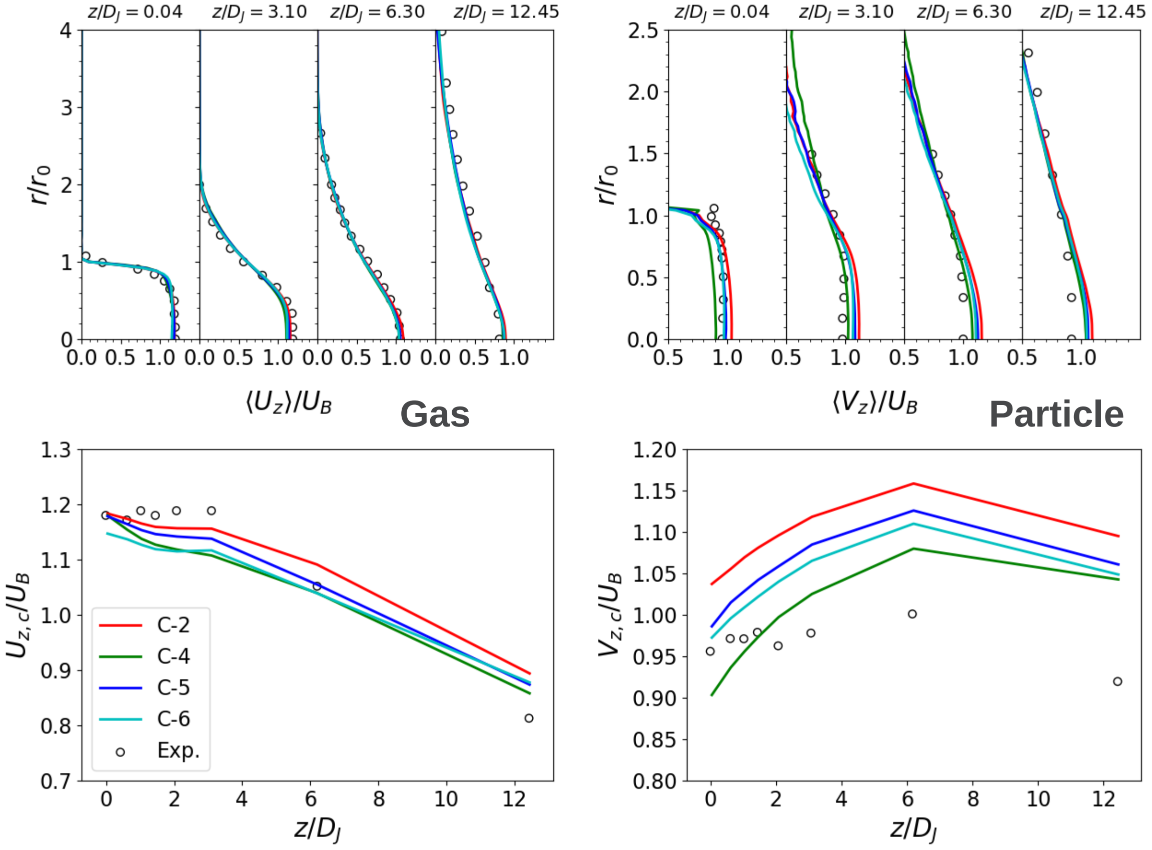


Case #	Injection loc., z_0/D_J	Coupling
C-1	-5	2-way
C-2	-5	4-way
C-3	-2	2-way
C-4	-2	4-way

$\boldsymbol{L = 1.0}$; $\bar{\theta}_p = 0.00047$; $St = 11.6$

- → Classification by Elghobashi (1991): limit between dense/dilute suspension. Collisions may be neglected.
- → Current results: 4-way coupling improved particle distribution and centerline velocities.

PARTICLE-LADEN JET: INJECTION PARAMS.



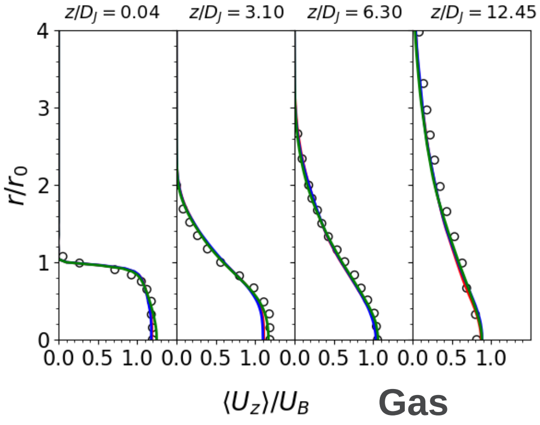
Case #	Injection loc., z_0/D_J	Injection vel. V_0/U_B
C-2	-5	0.7
C-4	-2	0.7
C-5	**-3.7**	**0.7**
C-6	-5	0.5

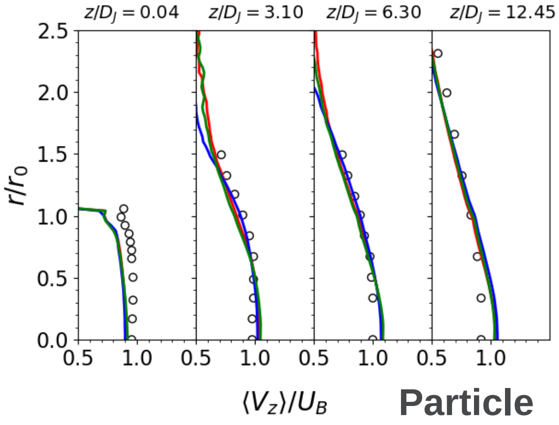
$L = 1.0;\ \bar{\theta}_p = 0.00047;\ St = 11.6$

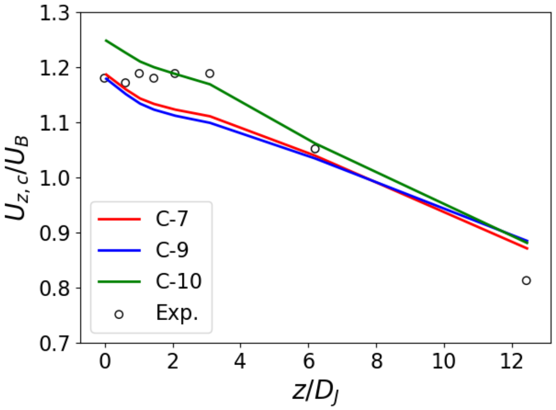
$z_0 \downarrow$: Further upstream

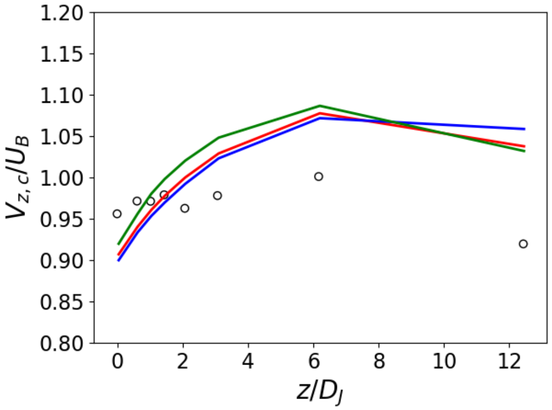
→ By changing particle injection location and velocity, predicted exit velocity can be improved.

PARTICLE-LADEN JET: HYDRODYNAMIC FORCES AND PARTICLE DISTRIBUTIONS







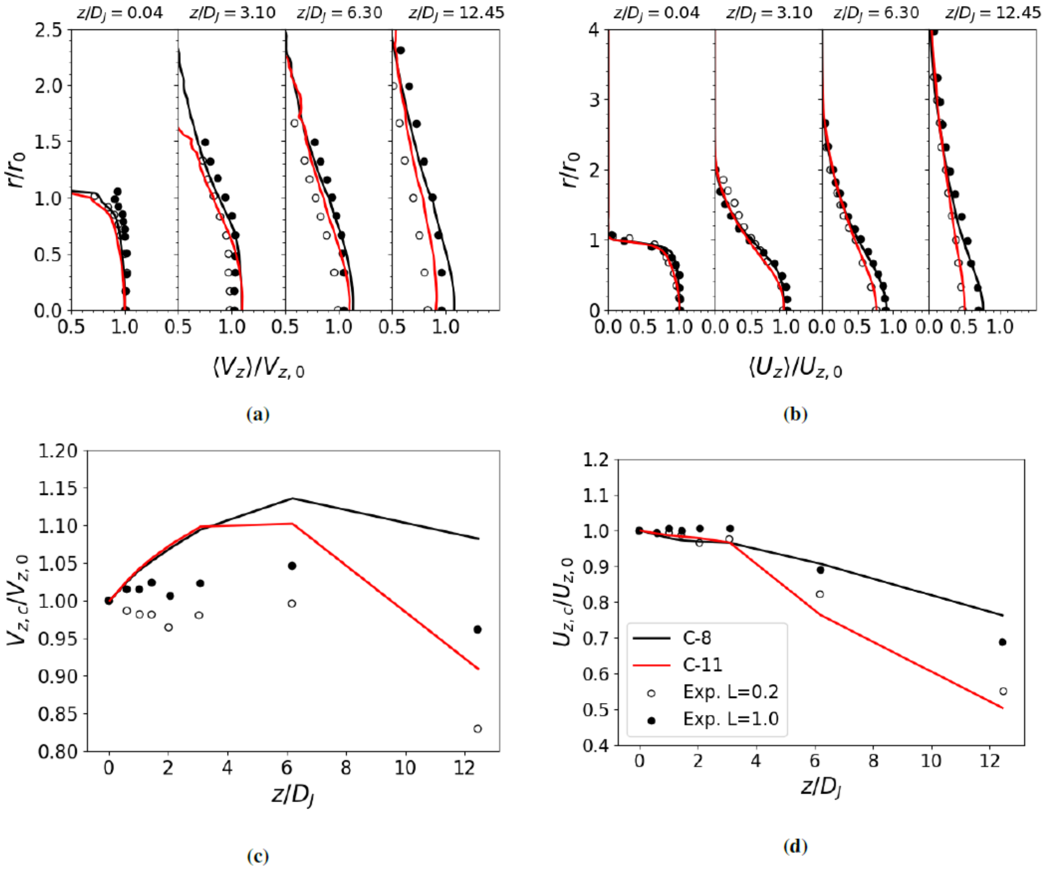


Case #	Forces	Distribution
C-7	**Drag**	**Non-uniform**
C-9	All HD	Non-uniform
C-10	Drag	Uniform

$L = 1.0;\ \bar{\theta}_p = 0.00047;\ St = 11.6$

→ Only drag plays a significant role, with other forces (pressure-gradient, added mass, shear-induced lift) having negligible effect on the mean flow.

PARTICLE-LADEN JET: MASS LOADING



(a) (b) (c) (d)

$L = 0.2 - 1;\ \bar{\theta}_p = 9.5 \times 10^{-5}; St = 11.6$

- → At lower loading ratio (L), particles and gas phase tend to decelerate more downstream
- → Current method can capture the difference in momentum transfer for cases with differing mass loading ratios, with numerical results showing the same trends as in the experiment.

PARTICLE-LADEN JET

- Further analysis not shown in this presentation:
  - Particle sub-cycling: did not have significant effect on flow statistics.
  - Grid sensitivity: Improving grid resolution by doing p-refinement (increasing N) did not affect results → gas-phase is well resolved.
  - Initial particle distribution: Assuming uniformly-distributed particles only affected the near-field, while far-field mean flow statistics are not very much affected by initial particle distribution.

Colmenares, J. D., Ameen, M. M., Wu, S., & Patel, S. (2021). Large Eddy Simulation of Turbulent Particle-laden Jets using the Spectral Element Method. In *AIAA Scitech 2021 Forum* (p. 0635).

CONCLUSIONS

- Current EL-SEM approach was used successfully to model turbulent single-phase and particle-laden jets.
- Varying particle injection location and velocity helped improve flow prediction.
- Collisions affected the flow, other simulation parameters did not.
- Cause for discrepancy between numerical and experimental results is unclear:
  - Missing information about the experimental flow:
    - Prior to exiting the inlet pipe (e.g. swirl)
    - Within the jet
  - Missing forces in the model:
    - History forces
    - Tangential component of collision forces
    - Realistic collisions (stiffness and restitution coefficients)
- Future work will include missing physics. More detailed experiments would help.

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THANK YOU!

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