Modeling Enhancements for Eulerian-Eulerian Two-Fluid Methods in Compressible Particle-Laden Flows with Plume-Surface Interaction Applications

Dr. Raymond Fontenot[*1]
Joseph Talbot[1]
Dr. Manuel Gale[1]
Dr. Ranjan Mehta[1]
Dr. Jesse Capecelatro[2]

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*** Primary/Corresponding Author**
1: CFD Research
2: University of Michigan

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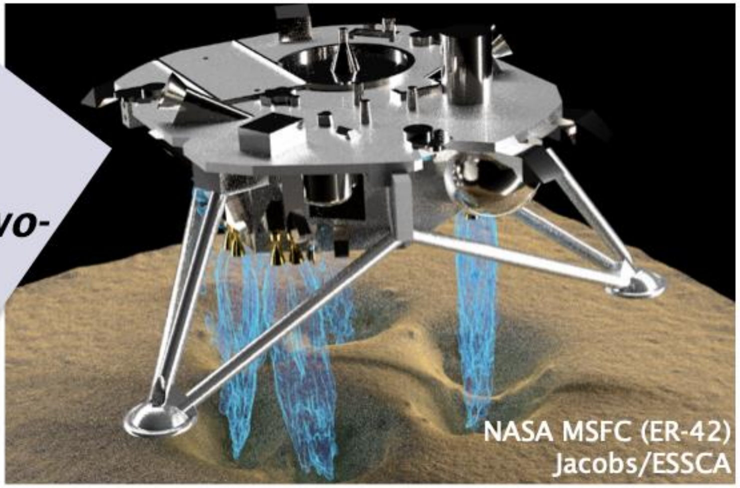
Multi-Scale Approach is Needed to Improve Flight-Scale Simulations

Increasing length scale

Full-landing site:
Eulerian-based two-fluid model



- Description: Treats gas and solid as a continuous fluid
- **# particles: cost *independent* of number of particles!**
- Relies heavily on constitutive models to account for important gas-particle and particle-particle interactions that **have not yet been developed or tested under relevant PSI conditions!**

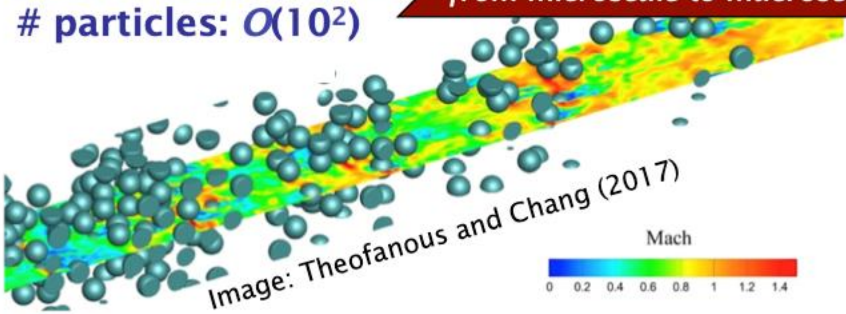
Intermediate scale:
Eulerian-Lagrangian

- Description: Tracks individual particles and resolves collisions
- **# particles: *O*(10^8)**
- Requires models for gas-particle microphysics (e.g. drag)

Particle-scale: *DNS*

- Direct solution to governing equations
- **# particles: *O*(10^2)**

Physics can be lost when going directly from microscale to macroscale!



Evaluation and Calibration of Models: E-E and E-L Approaches

1. Limited experimental (validation) data available to characterize gas/particle/particle interactions in propulsive landing conditions
2. Limited data for mixtures with well-characterized polydispersity and supersonic flow – PFGT.
3. In shock-particle interactions, additional (unresolved) velocity fluctuations appear at particle-scale due to wakes: Pseudo-Turbulent Kinetic energy (PTKE)
   a) Not included in the E-E methodology
   b) Effect of this term in high-speed flows with particles expected to be first-order
      i. Large possible contribution to total kinetic energy (between 30% and 100%)
      ii. Play a significant role in predicting choking and post-particle conditions
   c) Exists even in laminar flow regimes!

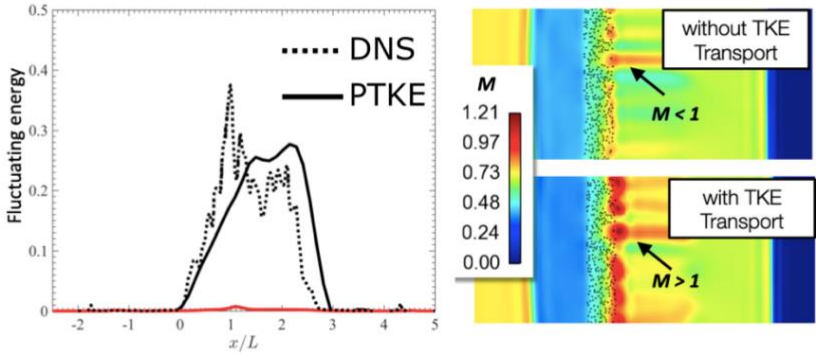


Figure 1. EL simulations of particle-shock interactions using the proposed PTKE transport model. Left: averaged fluctuating energy of the shock tube shown in Fig. 3. DNS (dashed line), EL with PTKE model (solid black line), EL without PTKE model (red line). Right: local Mach number from the EL simulation without the model (top) and with the model (bottom).

Pseudo-Turbulent Kinetic Energy

PTKE is defined as the trace of the PTRS (pseudo-turbulent Reynolds stress) [1]:

$$\rho_g k = 2Tr\left(\mathbf{R}_u\right)$$

where the PTRS, often neglected, arises from filtering the governing gas-phase equations [2]

$$\frac{\partial \alpha_g \rho_g \mathbf{u}_g}{\partial t} + \nabla \cdot \left(\alpha_g \rho_g \mathbf{u}_g \otimes \mathbf{u}_g\right) = -\nabla \cdot \left(\alpha_g \mathbf{R}_u\right) - \alpha \nabla p_g + \nabla \cdot \boldsymbol{\tau}_g + \alpha_g \rho_g \mathbf{g} + I_{s-g}^{mom}$$

$$\frac{\partial \alpha_g \rho_g e_{g,o}}{\partial t} + \nabla \cdot \left(\alpha_g \left(\rho_g e_{g,o} + p_g\right)\right) = -\nabla \cdot \left(\alpha_g \mathbf{u}_g \cdot \mathbf{R}_u\right) + \nabla \cdot \left(\mathbf{u}_g \cdot \boldsymbol{\tau}_g\right) + \nabla \cdot \mathbf{q}_g + \sum_{k=1}^{N_g} \left(\nabla \cdot \rho h V\right)_{g,k} + I_{s-g}^{mom} \cdot \mathbf{u}_g + I_{s-g}^{energy}$$

The equation of state is also modified to include PTKE:

$$p_g = (\gamma - 1)\left(\rho_g E - \frac{1}{2}\rho_g \mathbf{u}_g \cdot \mathbf{u}_g - \rho_g k\right)$$

[1] Peng, C., Kong, B., Zhou, J., Sun, B., Passalacqua, A., Subramaniam, S., and Fox, R. O., "Implementation of pseudo-turbulence closures in an Eulerian–Eulerian two-fluid model for non-isothermal gas–solid flow," *Chemical Engineering Science*, Vol. 207, 2019, pp. 663–671.

[2] Shallcross, G. S., Fox, R. O., and Capecelatro, J., "A volume-filtered description of compressible particle-laden flows,' *International Journal of Multiphase Flow*, Vol. 122, 2020, p. 103138.

Modeling PTKE

PTKE can be modeled in two ways: algebraic (incompressible [1] or compressible [2])

$$\frac{k}{E_g} = 2\alpha_s + 2.5\alpha_s\alpha_g^3 e^{-\alpha_s Re_s^{\frac{1}{2}}}$$

with:

$$E_g = 2\left|\mathbf{u}_g - \mathbf{u}_s\right|^2 \qquad Re_s = \frac{\alpha_g\rho_g|\mathbf{u}_g - \mathbf{u}_s|d_s}{\mu_g}$$

Transport [3]:

$$\frac{\partial \alpha_g\rho_g k}{\partial t} + \nabla\cdot\left(\alpha_g\rho_g\mathbf{u}_g k\right) = -\alpha_g\mathbf{R}_u : \nabla\mathbf{u}_g + \left(\mathbf{u}_s - \mathbf{u}_g\right)\cdot I_{s-g}^{mom} - \alpha_g\rho_g\epsilon_{PT}$$

PTRS — Drag — PTKE Dissipation

PTKE Dissipation Algebraic Model (others currently under study) [3]:

$$\epsilon_{PT} = (1 - f_\alpha)\frac{C_f k}{\tau_1} + f_\alpha\frac{C_f k}{\tau_2}$$

with:

$$\tau_1 = \frac{d_s}{\sqrt{k}} \qquad \tau_2 = \frac{d_s}{|\mathbf{u}_g - \mathbf{u}_s|} \qquad f_\alpha = \tanh\left(\frac{50\alpha_s}{max(\alpha_s)}\right) \qquad C_f \approx 52\alpha_s^{1.5}$$

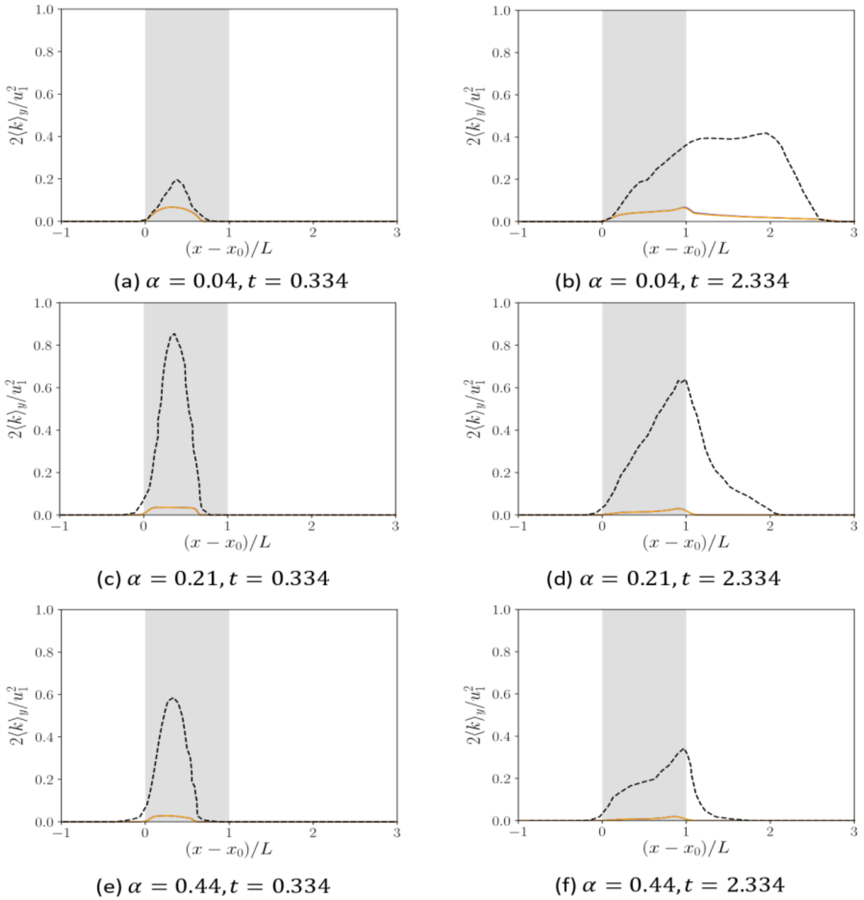
2D coefficient from VF-EL [3]

[1] Mehrabadi, M., Tenneti, S., Garg, R., and Subramaniam, S., "Pseudo-turbulent gas-phase velocity fluctuations in homogeneous gas-solid flow: fixed particle assemblies and freely evolving suspensions," *Journal of Fluid Mechanics*, Vol. 770, 2015, p. 210.

[2] Osnes, A. N., Vartdal, M., Omang, M. G., and Reif, B. A. P., "Computational analysis of shock-induced flow through stationary particle clouds," *International Journal of Multiphase Flow*, Vol. 114, 2019, pp. 268–286.

[3] Shallcross, G. S., Fox, R. O., and Capecelatro, J., "A volume-filtered description of compressible particle-laden flows,' *International Journal of Multiphase Flow*, Vol. 122, 2020, p. 103138.

PTKE with EL PTKE Dissipation Coefficient



- Utilized Euler-Lagrange (VF-EL)[1] dissipation coefficient in initial Euler-Euler (Loci/GGFS) [2] runs.
- PTKE dissipating too soon after particle curtain ends.
- Peak PTKE in EE significantly lower compared to EL.
- Investigated better dissipation coefficient for EE.

Transport, M-E Eqs, Loci/GGFS
Transport, E Src, Loci/GGFS
Shallcross, VF-EL

Energy Source only: $e_g = (\gamma - 1)\,\rho_g k V$ $\quad p_g = -\dfrac{\partial e_g}{\partial v}$

[1] Shallcross, G. S., Fox, R. O., and Capecelatro, J., "A volume-filtered description of compressible particle-laden flows,' *International Journal of Multiphase Flow*, Vol. 122, 2020, p. 103138.

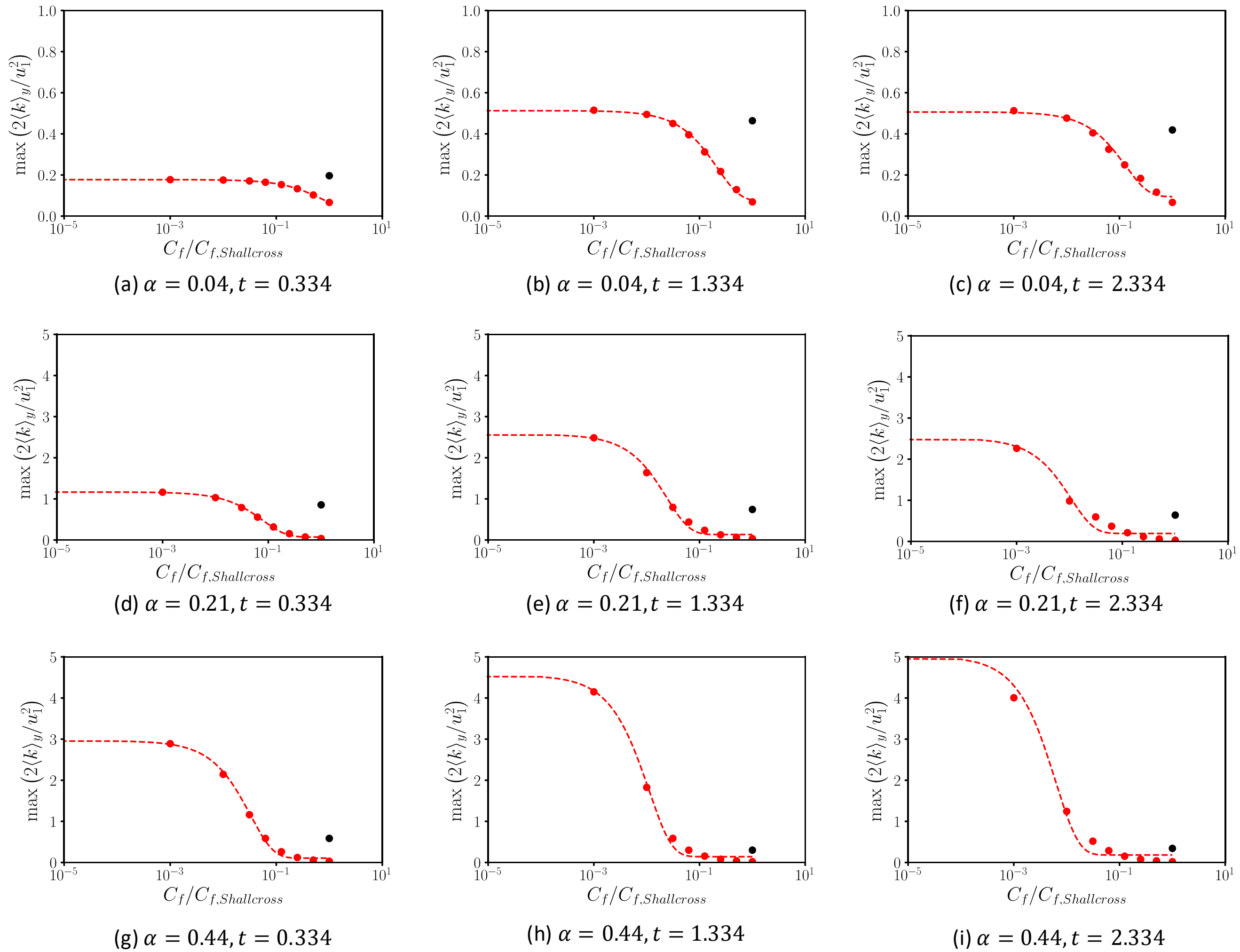
[2] Gale, M., Mehta, R. S., Liever, P., Curtis, J., and Yang, J., "Realistic regolith models for plume-surface interaction in spacecraft propulsive landings," *AIAA Scitech 2020 Forum*, 2020, p. 0797.

PTKE Dissipation Coefficient

Investigation of PTKE Dissipation Coefficient C_f in Loci/GGFS:

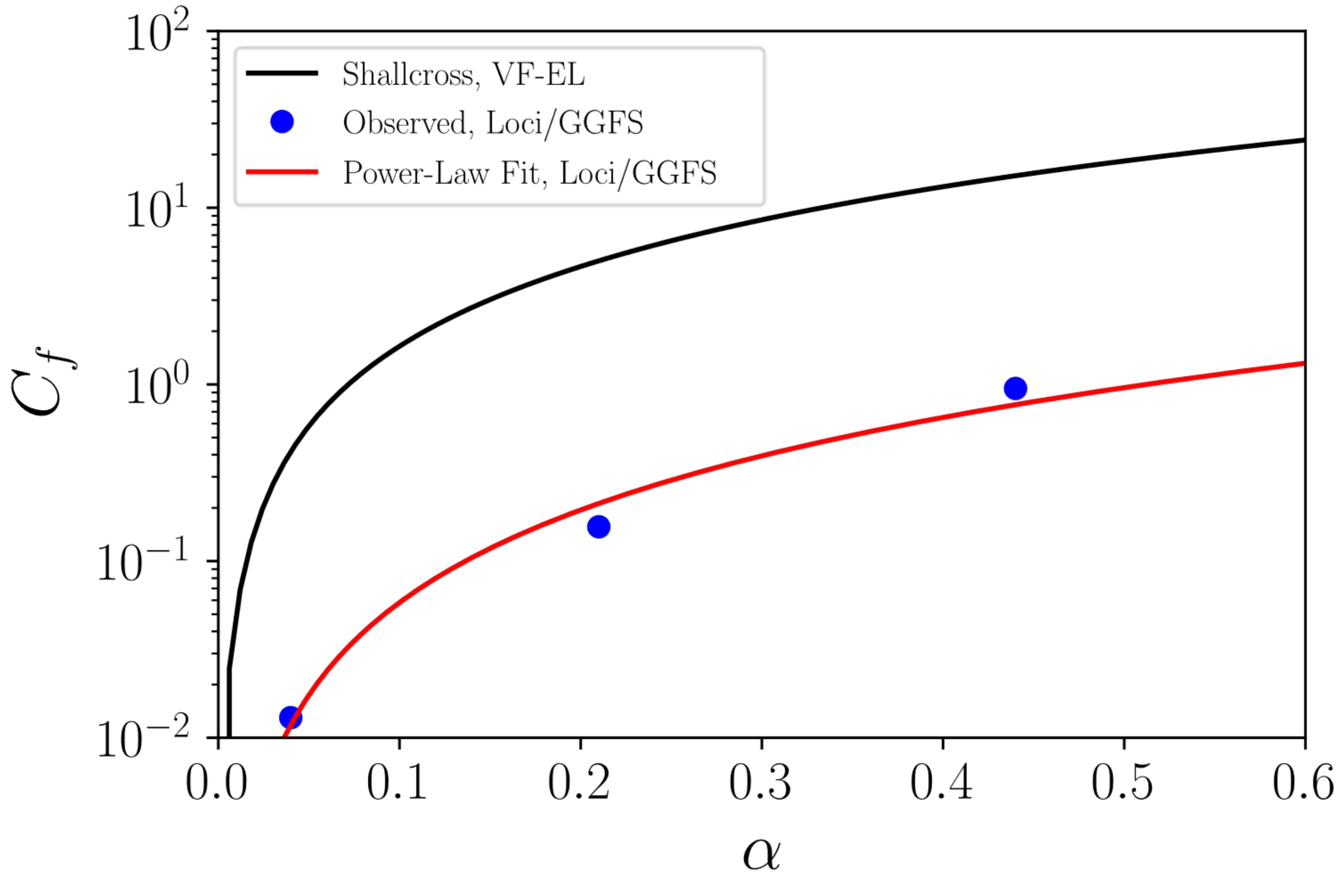
- Compare peak scaled-PTKE to determine C_f in Euler-Euler at each of the desired times.
- Choose closest C_f that produces similar peak PTKE as Euler-Lagrange simulation.
- Determined there is a maximum limit of PTKE that the model will produce.
- Determined a new nonlinear relationship between C_f and PTKE

● Loci/GGFS
● Shallcross VF-EL
– – – Exponential Fit



(a) $\alpha = 0.04, t = 0.334$
(b) $\alpha = 0.04, t = 1.334$
(c) $\alpha = 0.04, t = 2.334$
(d) $\alpha = 0.21, t = 0.334$
(e) $\alpha = 0.21, t = 1.334$
(f) $\alpha = 0.21, t = 2.334$
(g) $\alpha = 0.44, t = 0.334$
(h) $\alpha = 0.44, t = 1.334$
(i) $\alpha = 0.44, t = 2.334$

New Power-Law for PTKE Dissipation Coefficient in E-E



New Relationship for C_f:

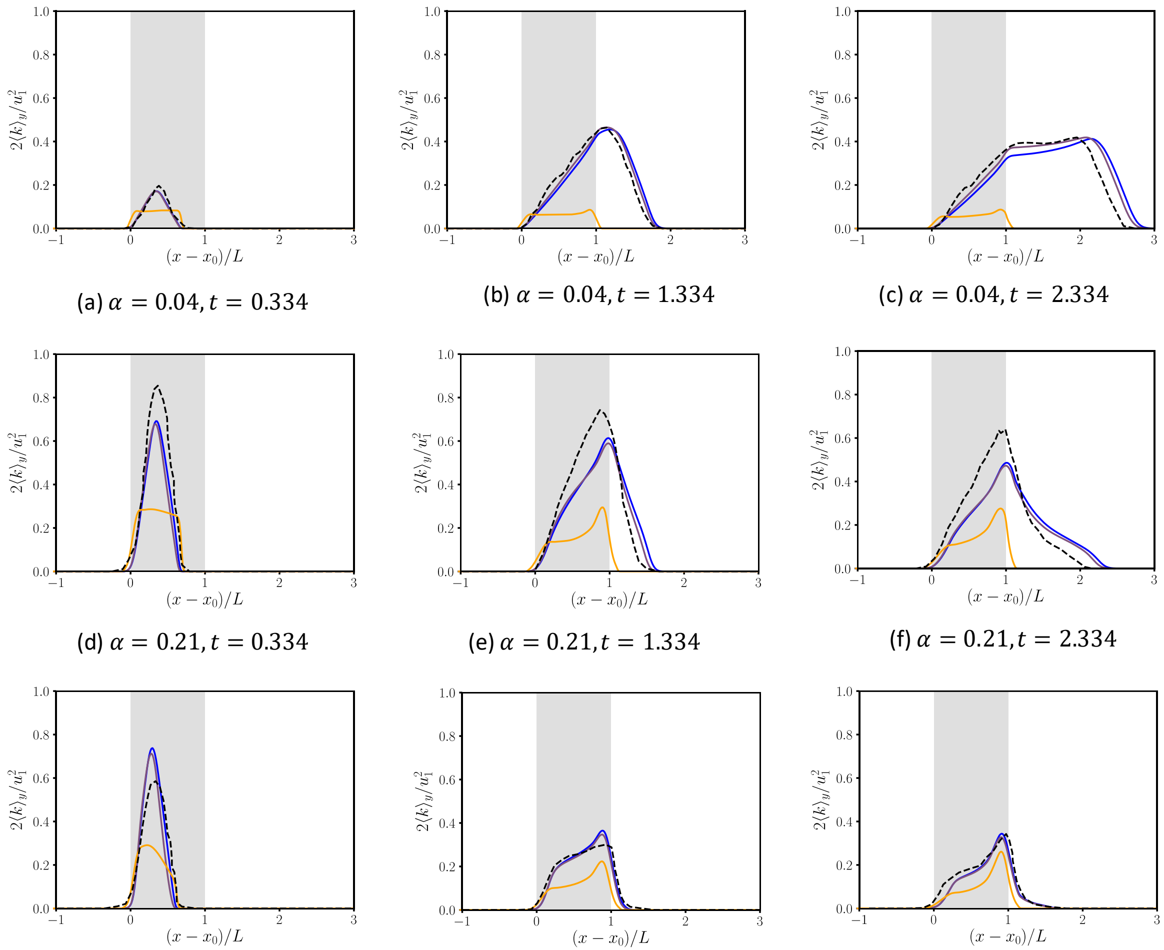
Euler-Lagrange: $C_f \approx 52\alpha_s^{1.5}$

Euler-Euler: $C_f = 3.20699\alpha_s^{1.7403}$

PTKE with New Dissipation Coefficient

Comparing PTKE with New PTKE Dissipation Coefficient C_f in Loci/GGFS:

- With optimal new fit for C_f, PTKE profiles for Loci/GGFS match much better to the VF-EL results
- Predict location of peak PTKE at each time in nearly same location as VF-EL
- Tail/cut-off of PTKE in Loci/GGFS close to VF-EL
- Correct change in dissipation at edge of particle curtain from slip velocity to velocity fluctuation
- Slight difference in coupling strategies



Transport, M-E Eqs, Loci/GGFS
Transport, E Src, Loci/GGFS
Algebraic, M-E Eqs, Loci/GGFS
Shallcross, VF-EL

(a) $\alpha = 0.04, t = 0.334$ (b) $\alpha = 0.04, t = 1.334$ (c) $\alpha = 0.04, t = 2.334$

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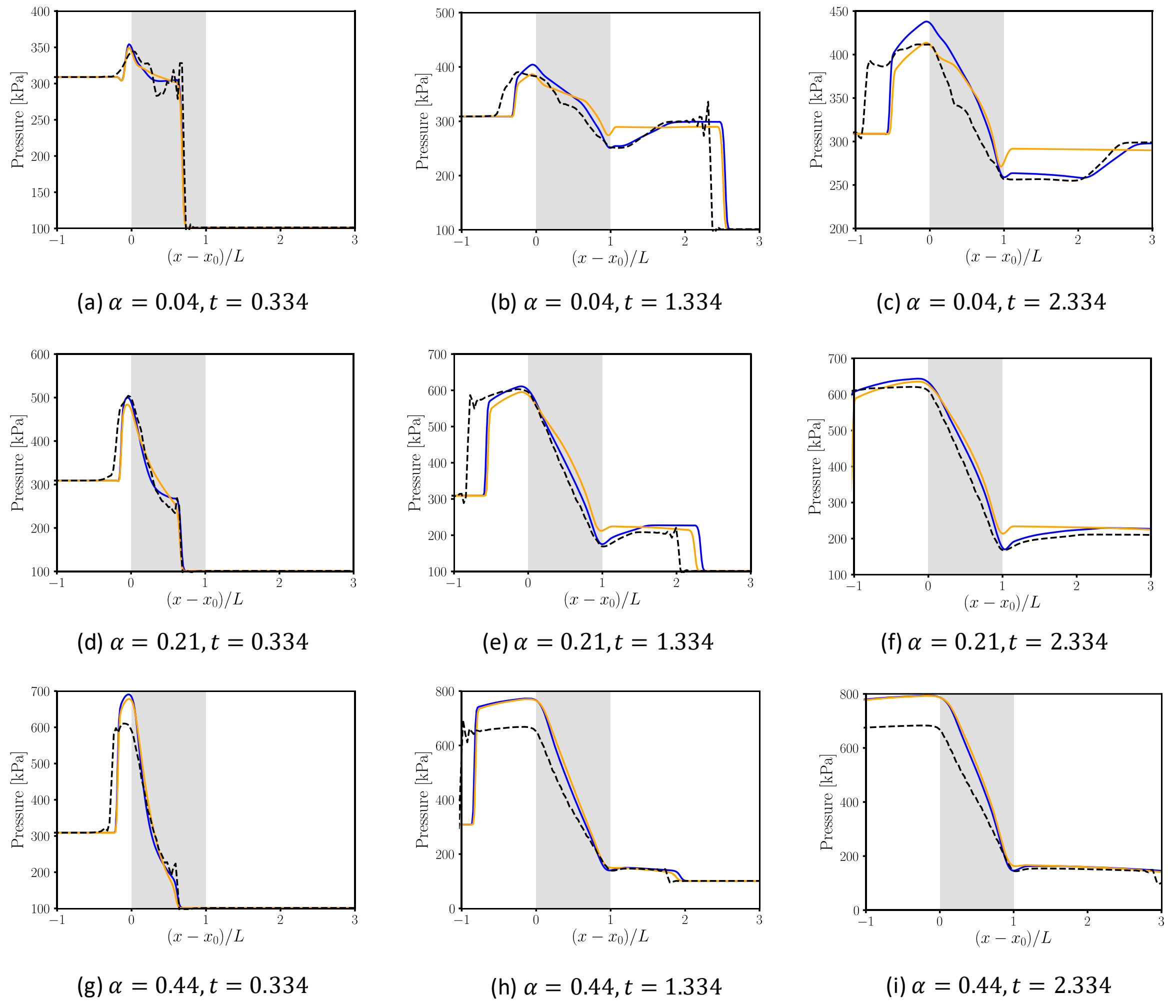
[3] Shallcross, G. S., et al. (2020). "A volume-filtered description of compressible particle-laden flows." International Journal of Multiphase Flow **122**: 103138.

Pressure Profiles:

- PTKE modifies the pressure field, as expected. Noticeable differences in field when not coupling PTKE to equations.
- Reflected shock incorrect in Loci/GGFS, due to flux function and shock pressure discretization.
- Trailing edge pressure from Loci/GGFS has excellent agreement with VF-EL [3].



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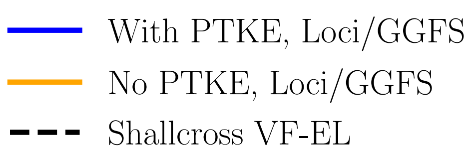
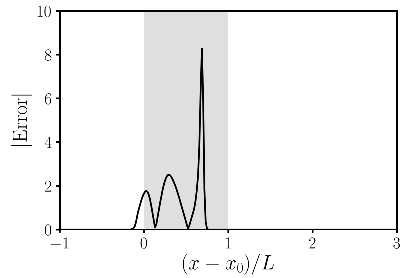


[3] Shallcross, G. S., et al. (2020). "A volume-filtered description of compressible particle-laden flows." International Journal of Multiphase Flow **122**: 103138.

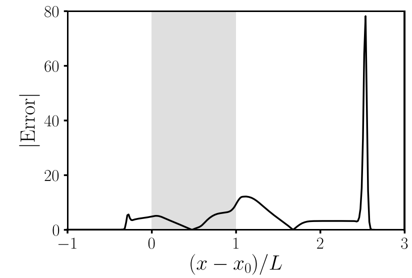
Error of Computed Pressure with PTKE

Error in Pressure Profiles:

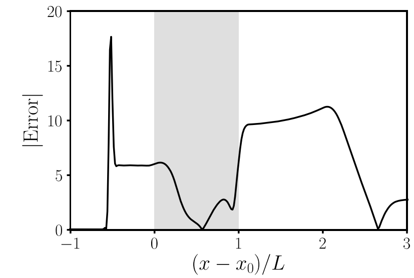
- At early times, largest error due to handing of reflected and downstream traveling shock.
- Within curtain, the difference in pressure is on average 10%.
- At trailing edge, the difference in the pressure field can be as large as 22% for $\alpha = 0.21$.
- Excluding PTKE for these flows is very detrimental to the flow field.



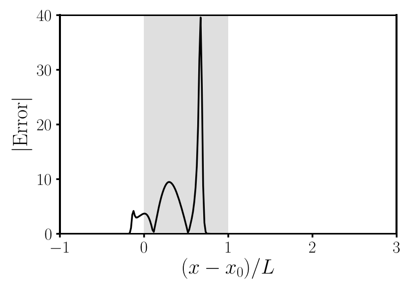
(a) $\alpha = 0.04, t = 0.334$



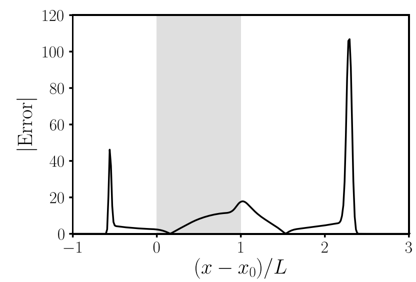
(b) $\alpha = 0.04, t = 1.334$



(c) $\alpha = 0.04, t = 2.334$



(d) $\alpha = 0.21, t = 0.334$



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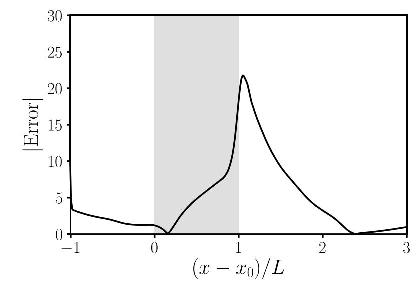
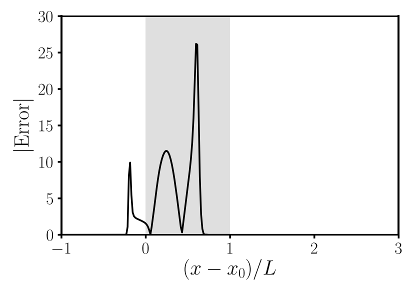


(f) $\alpha = 0.21, t = 2.334$



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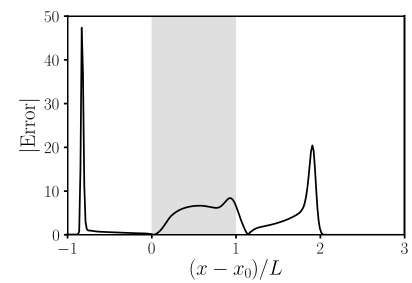
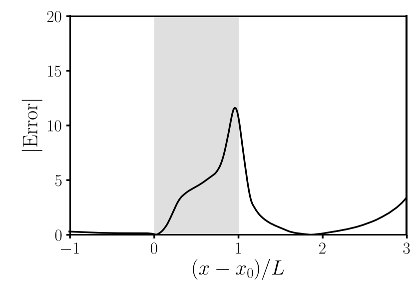


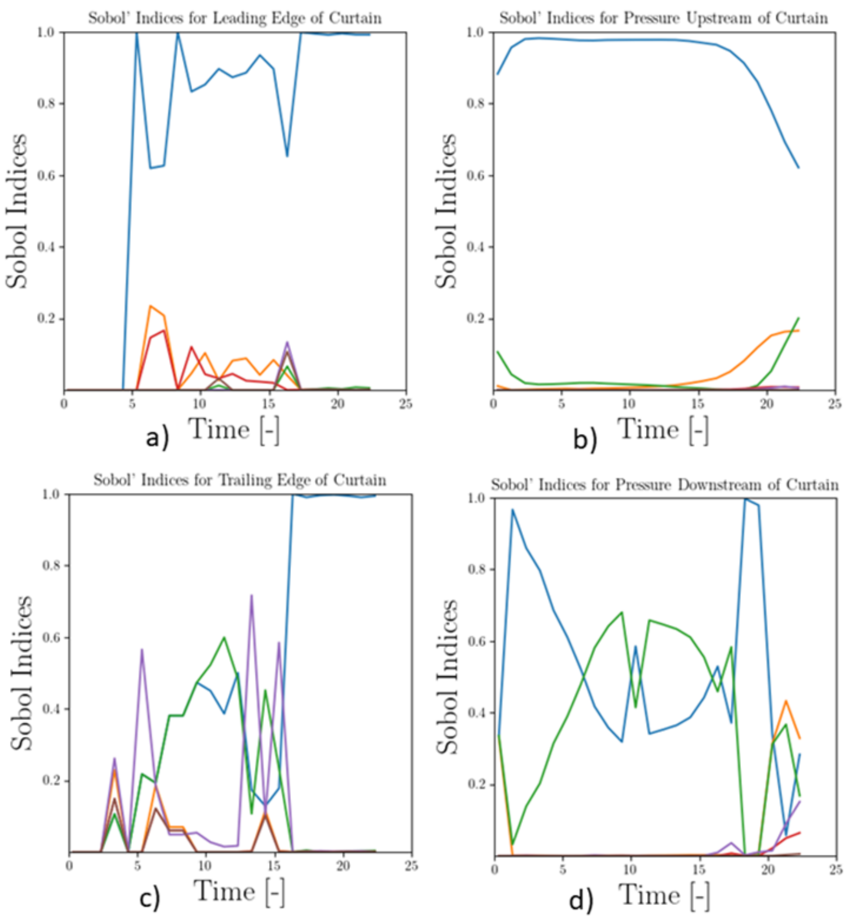
(h) $\alpha = 0.44, t = 1.334$

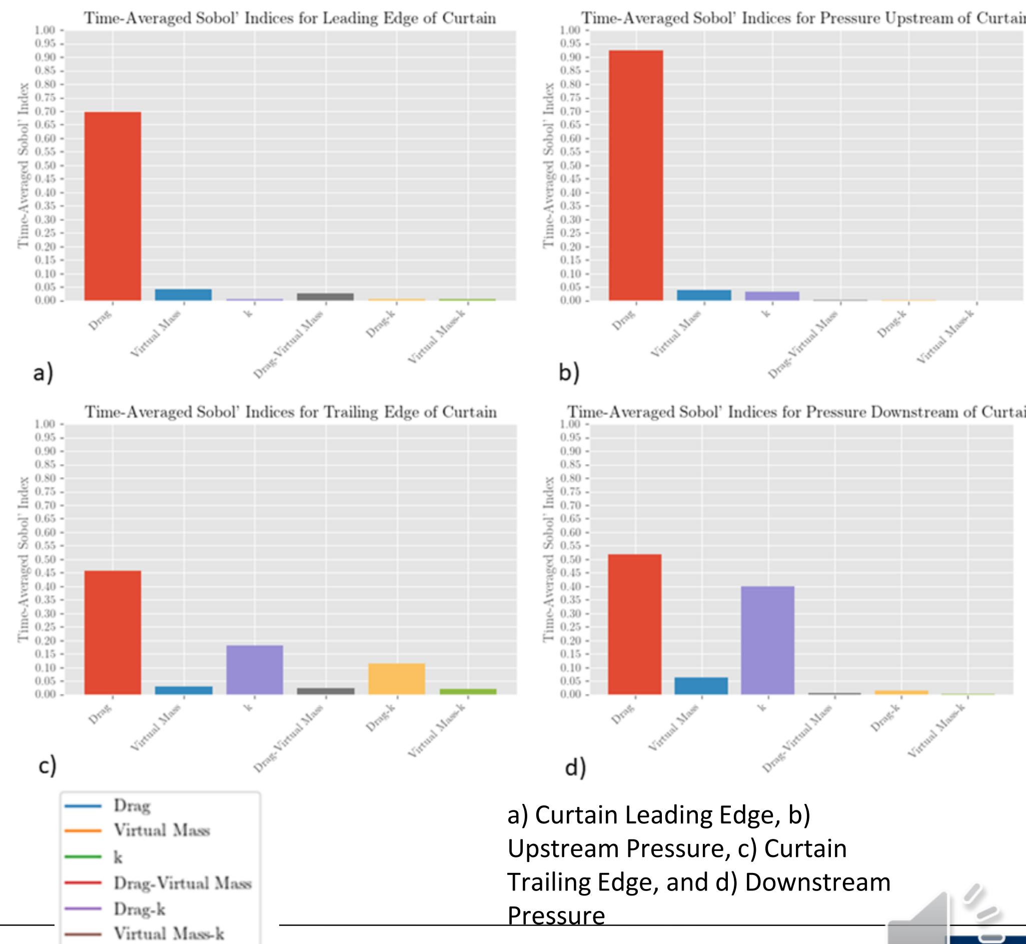


(i) $\alpha = 0.44, t = 2.334$

Sensitivity Analysis of Shock-Particle Curtain for Drag, Virtual Mass, and PTKE

- Input uncertain parameters (20% form nominal, uniform): drag, PTKE, and virtual mass sources in governing equations in Loci/GGFS
- Level one analysis with 31 simulations (Sparse Grid Adaptation in Parameter Space, with Stochastic Expansion methods) with DAKOTA
- Volume fraction α = 0.21 particle curtain for 22.334 non-dimensional time to allow for curtain spread
- Sensitivity of leading/trailing edge location and pressure at (dx=1curtain width) before/after curtain
- Drag most important for upstream
- Downstream drag and PTKE both important





a) Curtain Leading Edge, b) Upstream Pressure, c) Curtain Trailing Edge, and d) Downstream Pressure

A-priori assessment of PTKE for PSI-Related Cases

- Major questions remain on how important PTKE is in PSI environments
  - Probably not a major factor within a crater
  - Could be a factor in enhancing shearing/ejecta away from crater
- Two cases are studied to give insight and investigate parameter space where PTKE may be active:
  - Plume impingement of underexpanded jet on a granular bed (see Figure below)
  - Apollo Lander (2D axisymmetric simulation) (data courtesy of the PSI team at NASA MSFC ER42)
- In order to examine regions of high importance in these cases, PTKE was parameterized by slip Mach number, granular-phase Reynolds Number, and slip kinetic energy

$$M_{slip} = \frac{|\mathbf{u}_g - \mathbf{u}_s|}{\sqrt{\gamma_g T_g R_g}}$$

$$Re_s = \frac{\alpha_s \rho_g |\mathbf{u}_g - \mathbf{u}_s| d_s}{\mu_g}$$

$$E_g = \frac{1}{2}\left|\mathbf{u}_g - \mathbf{u}_s\right|^2$$

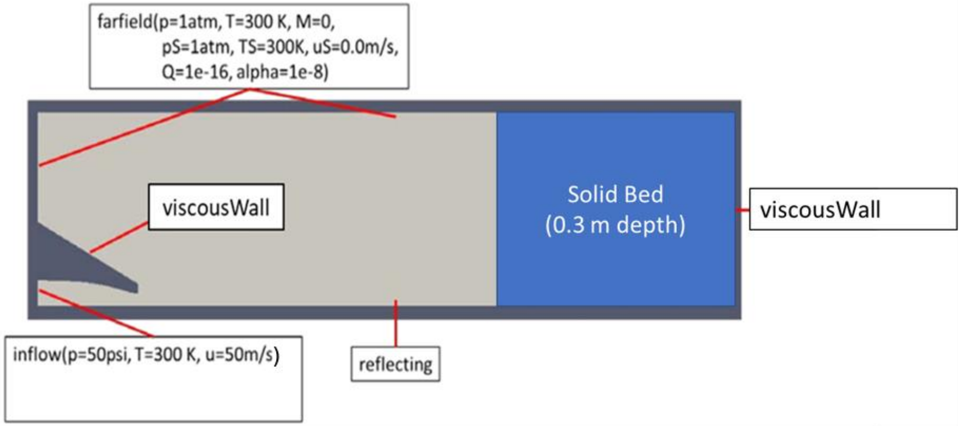
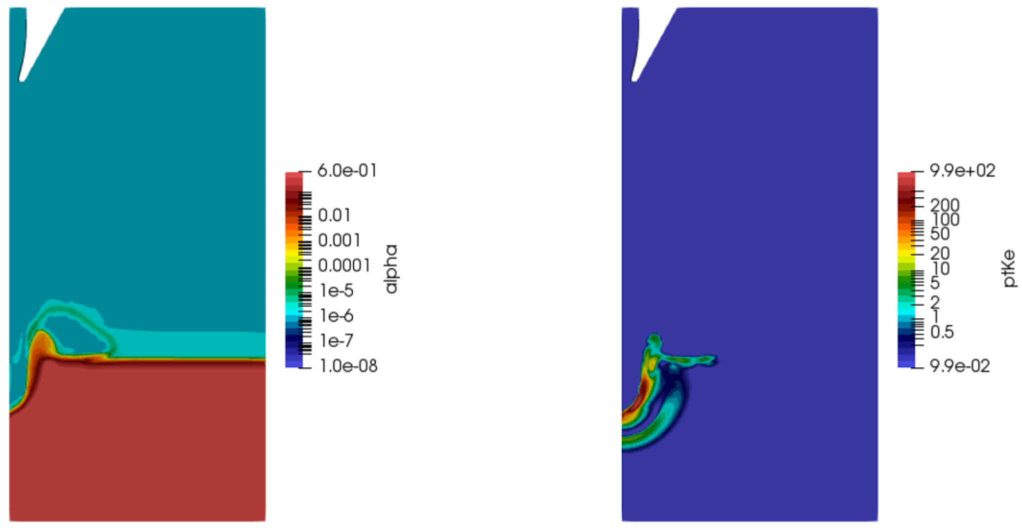
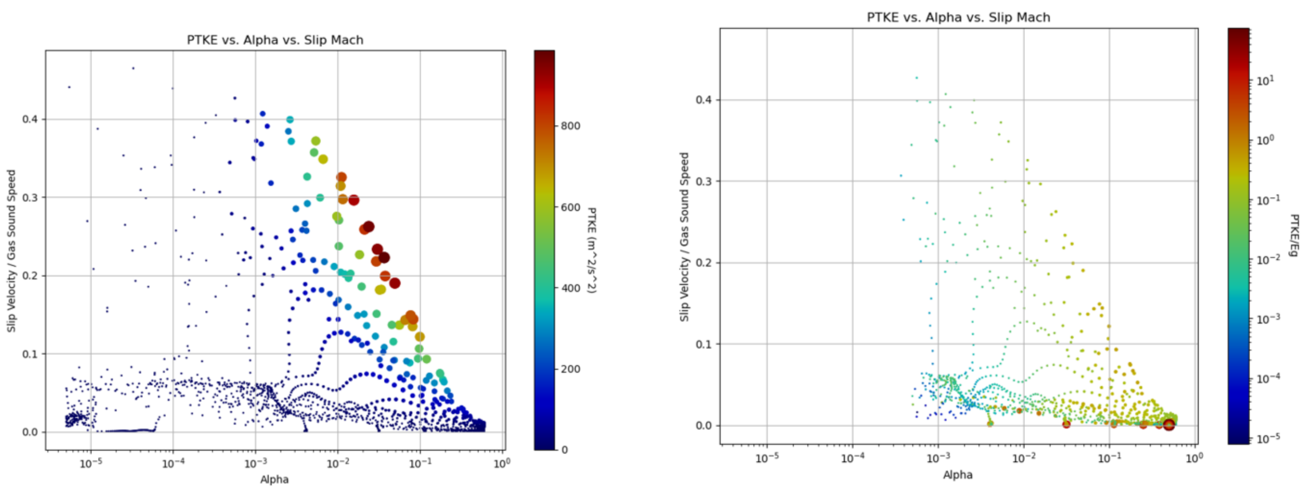


Figure: Underexpanded PSI Geometry

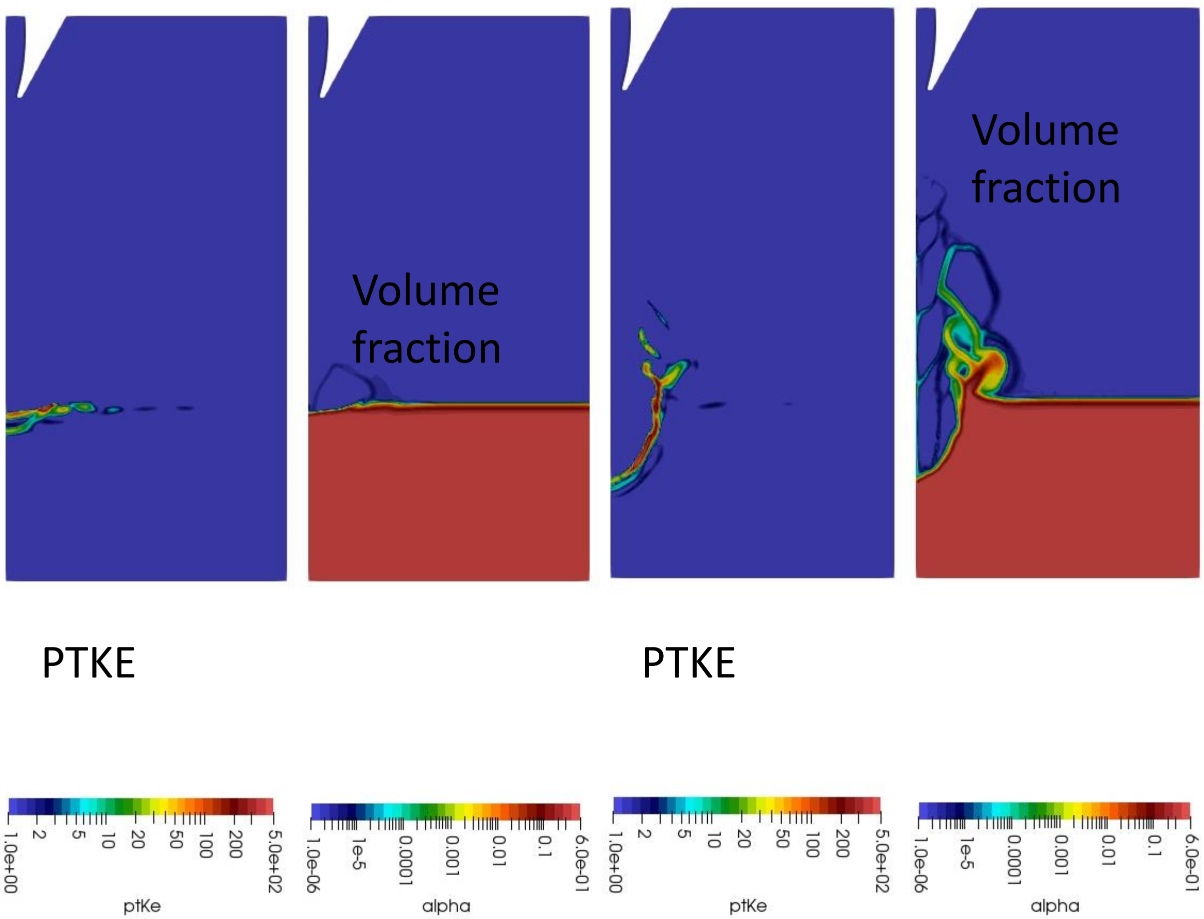
Contours of
α and PTKE



Parametrics



Plume Impingement: Algebraic PTKE Discussion



Early Time

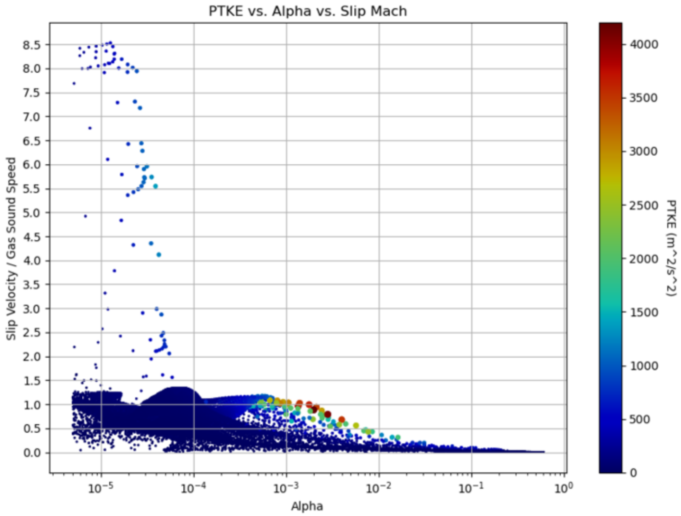
Later Time

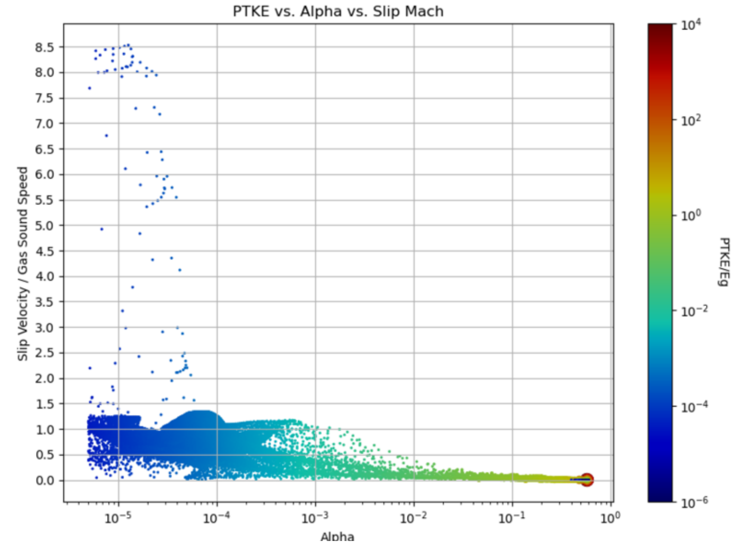
1. PTKE significant in expected regions
2. Initially when shearing is happening near the surface
3. Later on when significantly larger relative velocities between gas and granular phases happens with ejected material
4. At least source terms for PTKE seem reasonable !
5. Sink of PTKE is a different story

Apollo Lander Parametrics

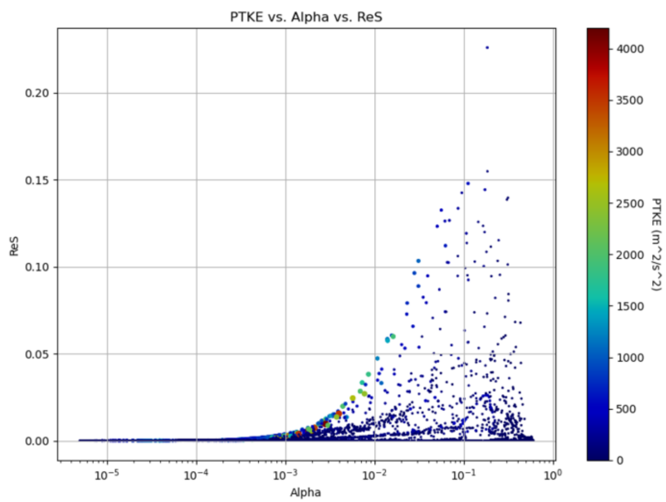
Unscaled

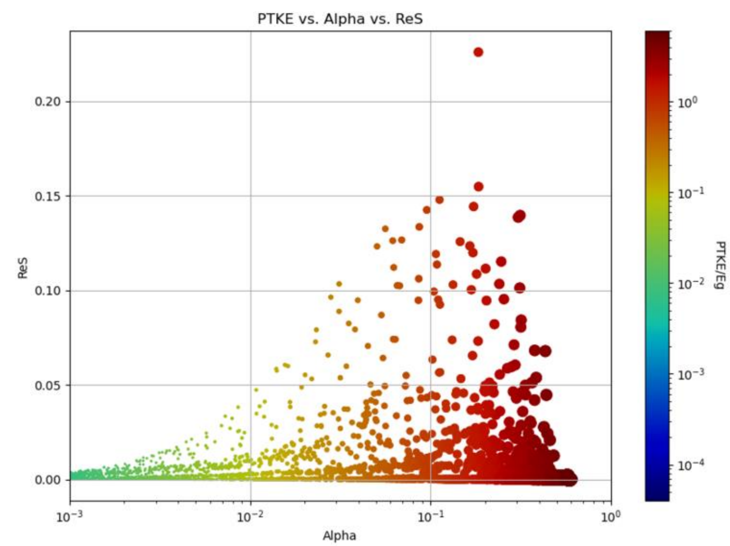
Scaled





M_{slip}





Re_s

α

α

Conclusions & Future Work

- PTKE transport for EE simulations was introduced
- Shock tube cases with 3 volume fractions were utilized to study implementation of PTKE
  - Compared to VF-EL simulations of Shallcross
  - New dissipation coefficient power-law for EE was developed to better match VF-EL data -> implying missing physics
- Algebraic PTKE was exercised on PSI-relevant simulations to determine parametric space of relevance for PTKE
  - Showed that PTKE may have greatest impact on crater where high M_{slip} is relative to α
  - Scaling by slip kinetic energy further points to PTKE being highest with lower M_{slip} in regions of high α
- Investigate improvements to PTKE dissipation to address deficiencies with current algebraic dissipation model

Acknowledgements

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