Numerical Simulation of the Aerodynamics and Acoustics of a Turbulent Wall Jet with Particulates

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Abstract

Understanding sound generation from high-speed multiphase jet flow is important for designing rocket engines and launch pad structures, as acoustic waves cause vibration loads and are a threat to the structural integrity. In this study, we numerically evaluated the far-field noise from a two-phase particle-gas supersonic wall jet. We choose the diameters of solid fuel particles within the flow to be 10 and 100 micrometers. Navier-Stokes equation with extra source terms from particle dynamics equations is solved numerically, and Ffowcs-Williams and Hawkings equations are implemented to evaluate far-field acoustics. The multiphase CFD code, Rocfluid-MP, runs parallel with approximately 100 processors on cluster Hipergator 2. We validate the results of the single-phase jet flows with measurement. We compare meanflows, turbulent statistics, acoustic source statistics, and statistics of acoustic pressure between the single and multiphase jets. We find that there are significant differences of predicted statistics between single and multiphase jets.

Computational Approach

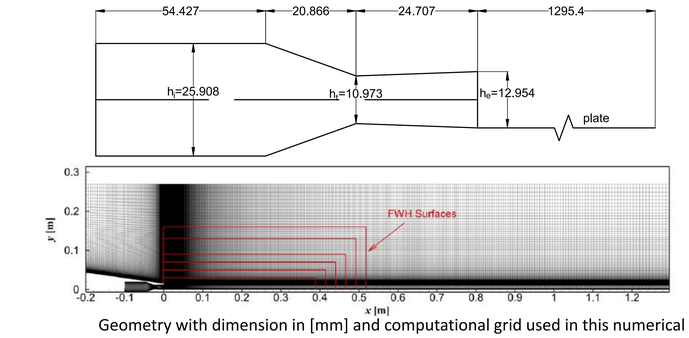
- Navier-Stokes equations coupled with Lagrangian particles dynamics equations through drag force and heat transfer terms are numerically evaluated using RocfluidMP in three different flow conditions in a supersonic jet.
- Particle dynamics equations:

$$\frac{d}{dt}\boldsymbol{x}_p = \boldsymbol{V}_p\,,\ \frac{\mathrm{d}}{\mathrm{dt}}\mathbf{V}_\mathrm{p} = \frac{\mathbf{V}-\mathbf{V}_\mathrm{p}}{\boldsymbol{\tau_u}}\,,\ \frac{d}{dt}T_p = \frac{T-T_p}{\tau_\theta}$$

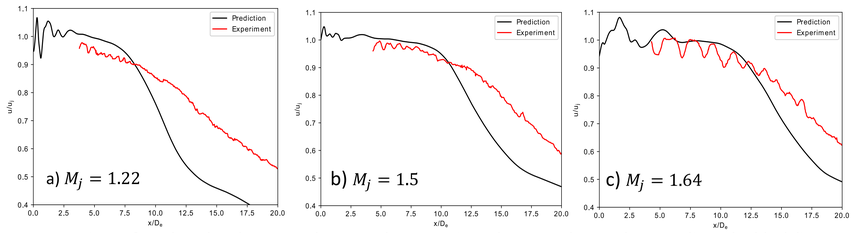
- Eulerian flow field variables are samples on the data surfaces at 100 kHz frequency, and time-dependent far-field noise at various locations are evaluated numerically using modified Farrasat's formulation[1].
- Modified Farrasat's formulation:

$$4\pi p'(\boldsymbol{x},t) = \int\left[\frac{\dot{l}_r}{cr}+\frac{l_r}{r}+\left(\frac{\dot{\rho}u_n+\rho\dot{u_n}}{r}\right)(1+\mathcal{M}_r)+\frac{\rho u_n}{r}\dot{\mathcal{M}}_r+\frac{\rho u_n u_r}{r^2}\right]_{ret}dS$$

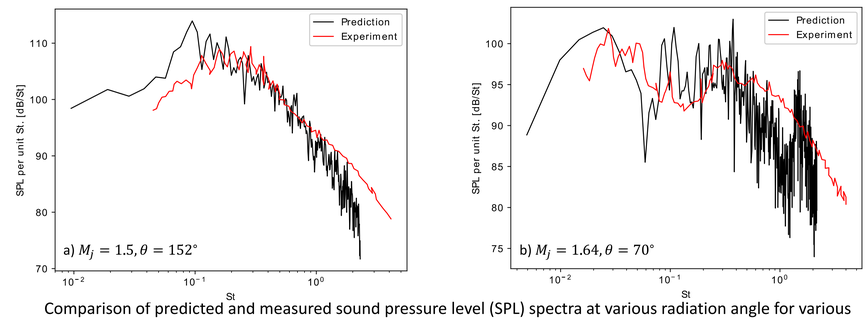
- Predicted single-phase flow field and far-field sound spectra are compared with measurement made by Mora et al[2].
- Flow field and far-field sound spectra of single phase jet flow and jet flow with two different size aluminum particles with the same mass loading are compared.



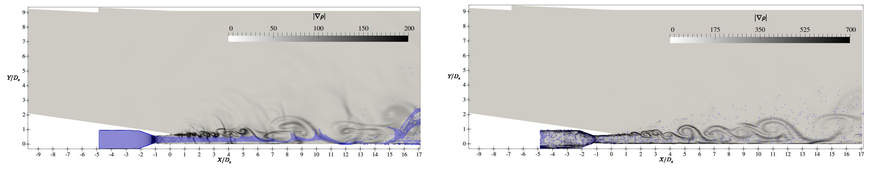
Geometry with dimension in [mm] and computational grid used in this numerical study.



Comparison of predicted and measured averaged streamwise velocity on the nozzle centerline. The black line represents the prediction and the red line represents the measurements..



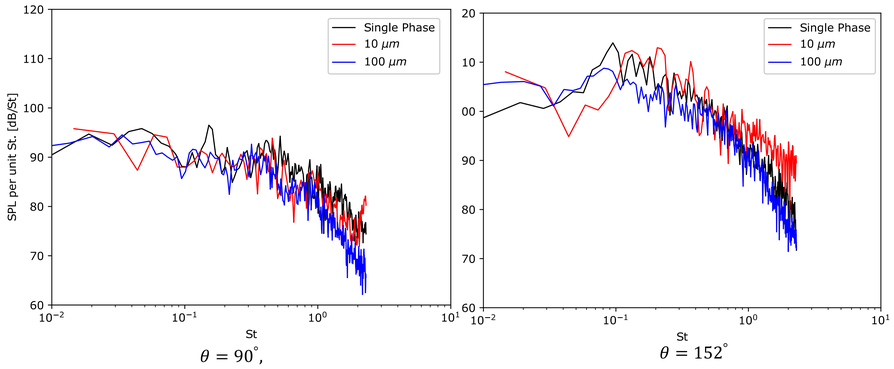
Comparison of predicted and measured sound pressure level (SPL) spectra at various radiation angle for various flow condition.



a) $d_p = 10\mu m$, 1 blue point represents 10 actual particles.

b) $d_p = 100\mu m$, 1 blue point represents 1 actual particle.

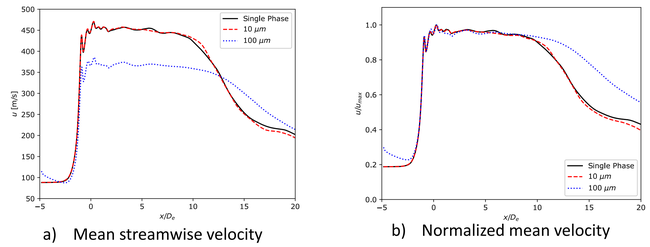
Comparison of instantaneous numerical Schlieren of flow with different particle diameters.
Blue points represent computational particles in the domain.



Comparison of SPL Spectra with single phase and flow with particles of diameters of $10\mu m$ and $100\mu m$.

Results

- Shocks are originated from nozzle throat and reflected on the internal wall, which justifies the inclusion of the nozzle geometry.
- Predicted mean velocity of the single phase jet at the nozzle exit and within the potential core has reasonable agreement with experiments, while the potential core length is underpredicted.
- The length of potential cores of jet flow with particles are longer than that of the flow without particle in it, while the mean velocity is less.
- Turbulent kinetic energy (TKE) is altered by particles in the flow, namely the peaks of TKE shift respect to the base flow.
- Predicted sound spectra at radiation angle of 70 and 152 degree are compared with measurement from Mora et al[2].
- Component of Lighthill stress tensor and cross correlation coefficient of horizontal separation distance from zero to one nozzle diameter are compared for the single-phase flow and the two-phase particle-gas flow.
- Comparison of spectra of sound pressure level (SPL) shows that particles, even at low mass loading, can change the noise characteristics.



a) Mean streamwise velocity

b) Normalized mean velocity

Comparison of time averaged streamwise velocity on the centerline of nozzle of single phase jet and two-phase jet with various particle diameters.

Summary and Conclusion

Summary

- FWH method based on implicit LES two-phase gas-particle simulation
- Predictions agree with previous experiments

Preliminary findings

- 10 μm particles have low impact on the flow statistics
- Jet flow with 100 μm particles shows lower mean velocity
- Particles attenuate high frequency noise at sideline direction
- Different size of particles shows different impact on the noise downstream

Future Work

- Three-dimensional simulation of two-phase gas-particle supersonic jet flow to capture three-dimensional turbulent break down
- Study the heated jet condition
- Validate with related experimental data
- Apply acoustic analogies to obtain better understanding of sound source

References

1. Farassat, F. and Casper, J., "Broadband Noise Prediction when Turbulence Simulation is Available - Derivation of Formulation 2B and its Statistical Analysis," Journal of Sound and Vibration, Vol. 331, No. 10, 2012, pp. 2203-2208. doi:10.1016/j.jsv.2011.07.044.
2. Mora, P., Baier, F., Kailasanath, K., and Gutmark, E. J., "Acoustics from a Rectangular Supersonic Nozzle Exhausting over a Flat Surface," The Journal of the Acoustical Society of America, Vol. 140, No. 6, dec 2016, pp. 4130-4141.

Nomenclature

- $\boldsymbol{x}$ – Position vector
- $\boldsymbol{V}$ – Velocity vector
- T – Temperature
- τ – Time scale

Subscriptions:

- P – particles values
- U – inertia
- θ – thermal