Northeastern University
College of Engineering

Advanced Computational and Experimental Methods in Cold Spray

Northeastern University

Cold Spray Additive Manufacturing Laboratory

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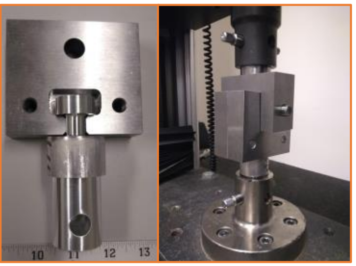
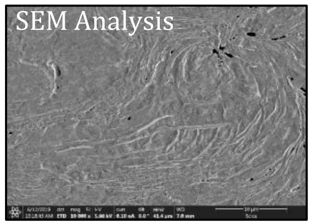
Cold Spray Action Team Meeting

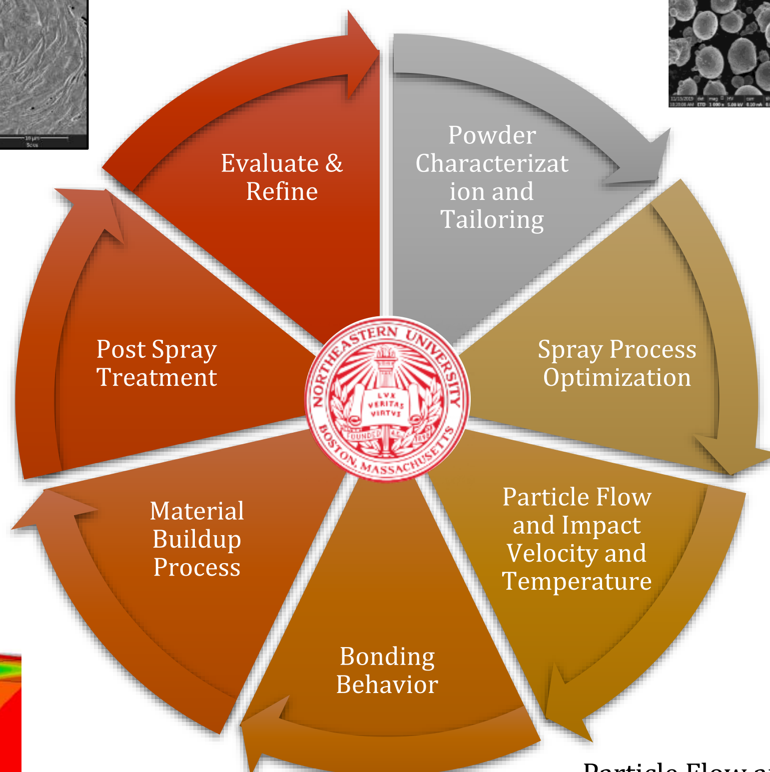
Online

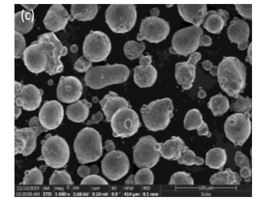
06/24/2020

Model Guided Materials & Process Development



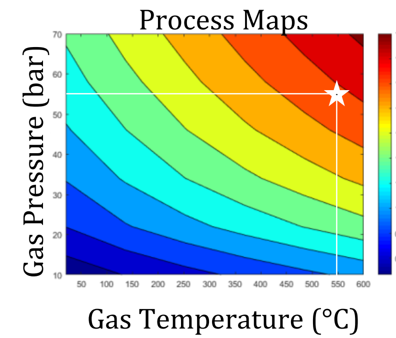


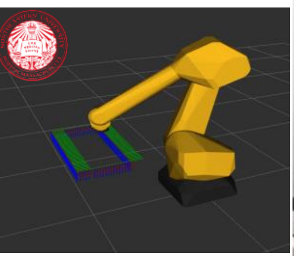


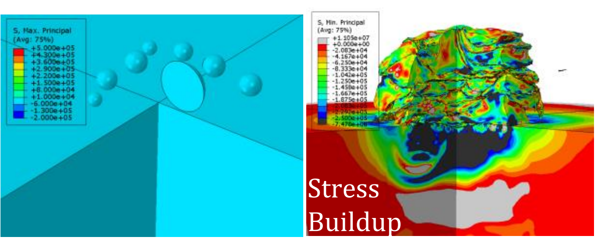


Powder Characterization

- Metallurgical
- Microstructural
- Mechanical
- Size distribution
- Shape distribution

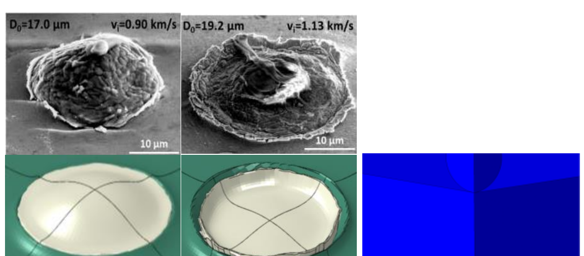




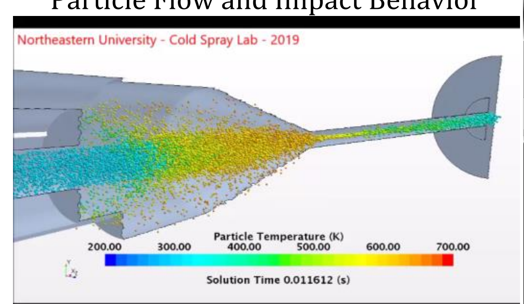


W. Xie, J.-H. Lee, UMASS

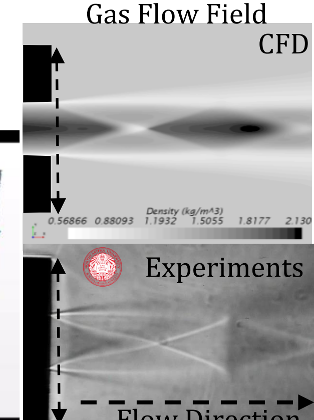
O. Chen, et al., NU



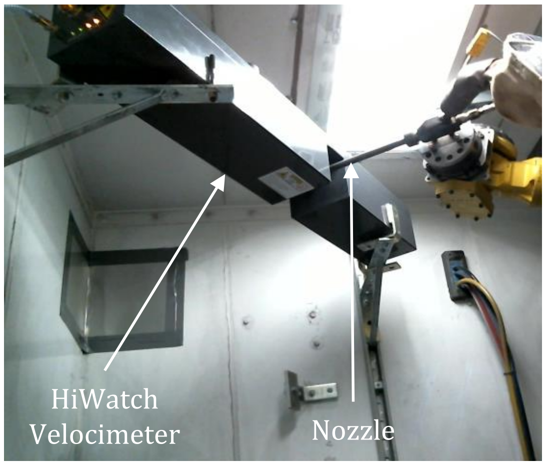
Particle Flow and Impact Behavior

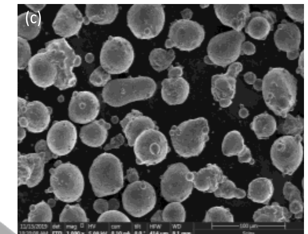


Gas Flow Field

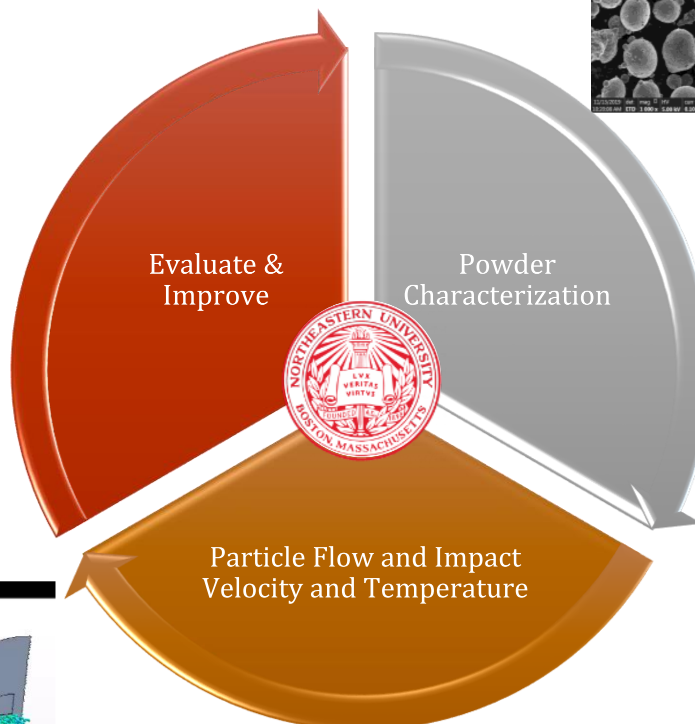


Today's Focus:
Factors Affecting Particle Flight and Impact Behavior

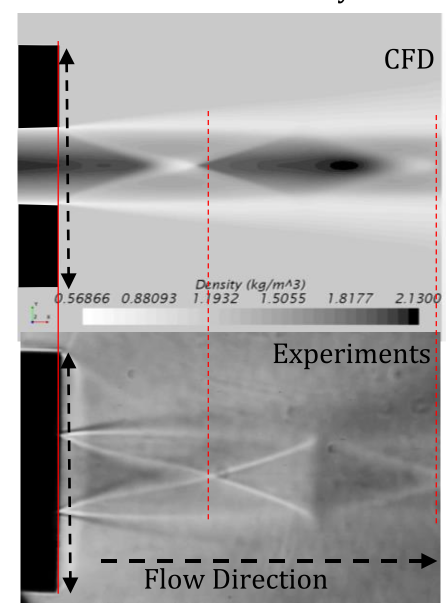




Powder properties of interest
- Metallurgical
- Microstructural
- Mechanical
- Size distribution
- Shape distribution

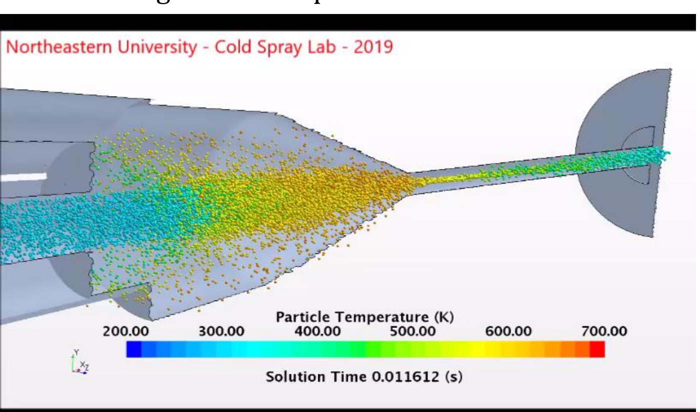


Gas Flow Field Analysis

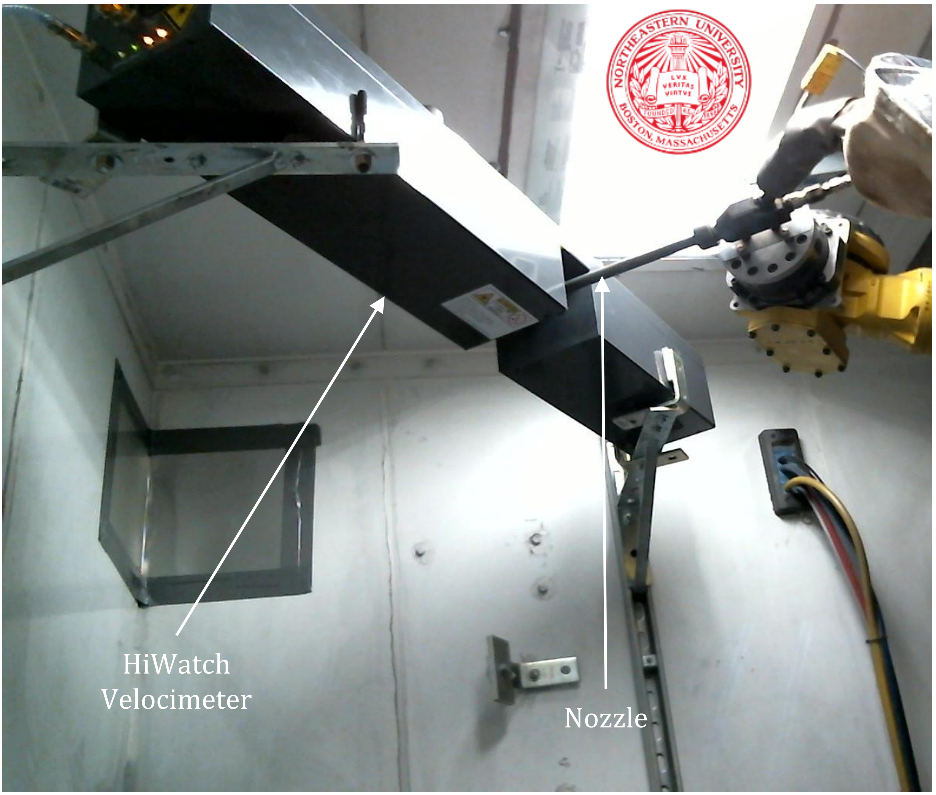


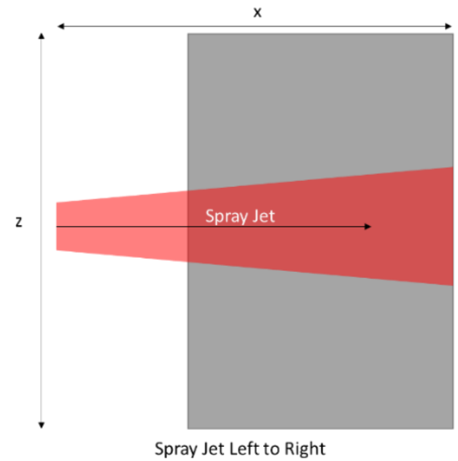
Gas Dynamics Validation Through Shock Diamond Measurement

Determining Particle Impact Conditions

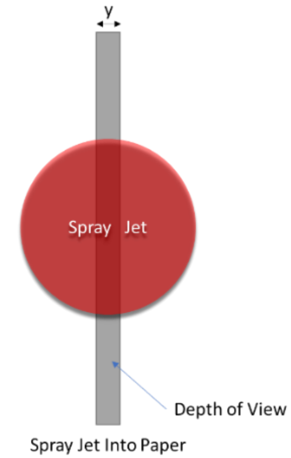


Particle Flight Velocity Measurements and Mismatch with CFD Simulations



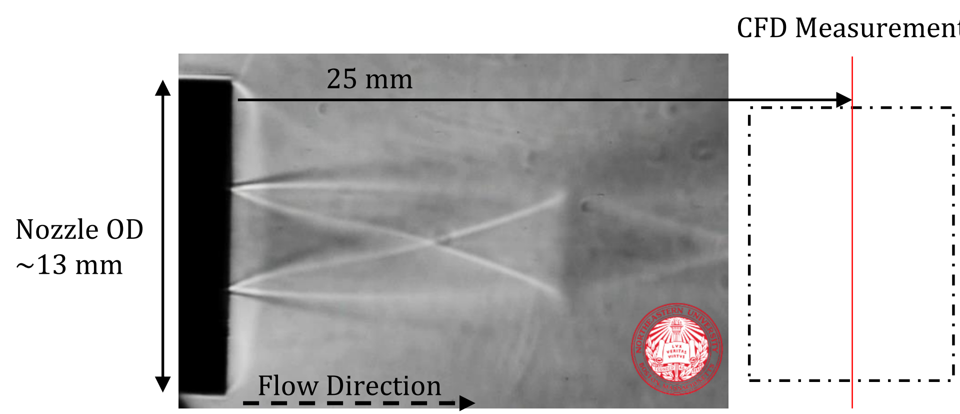


Measurement Window
X ~ 9.5 mm
Z ~ 14 mm



Field of View
Y = 0.4 mm

Measurement Limitations
Max Velocity: 1,400 m/s
Max d_p: 5 µm
Particle size distribution different than actual

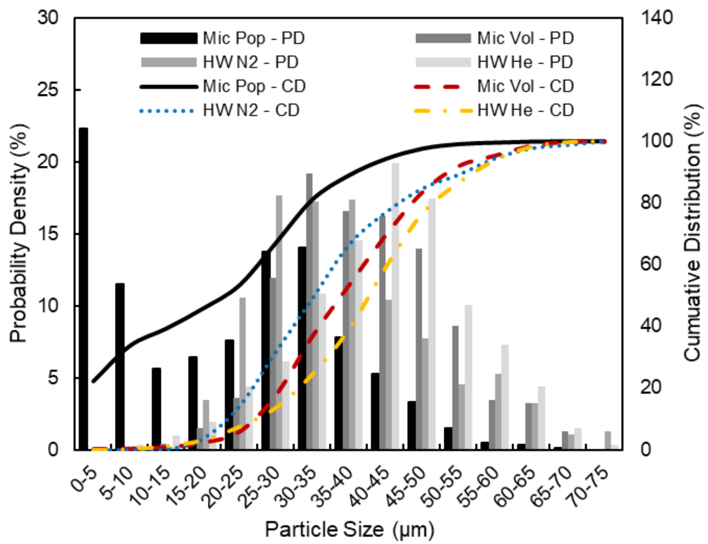


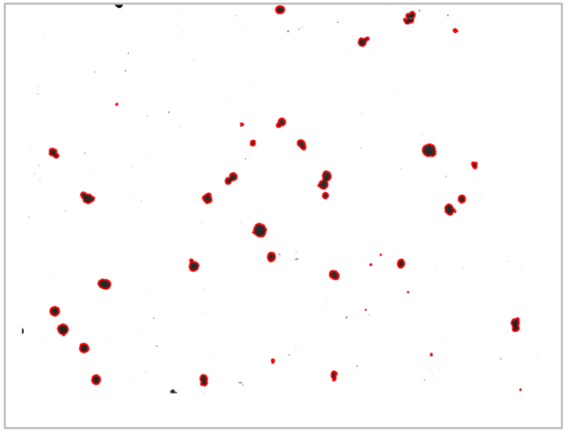
Schlieren Image Taken at NU Showing Shock Diamonds

Particle size distribution for Al and Cu through transmission microscopy.

VRC System
Nozzle 71
Helium
35 bar, 425 C
Mil Spec Al6061 Powder
Valimet

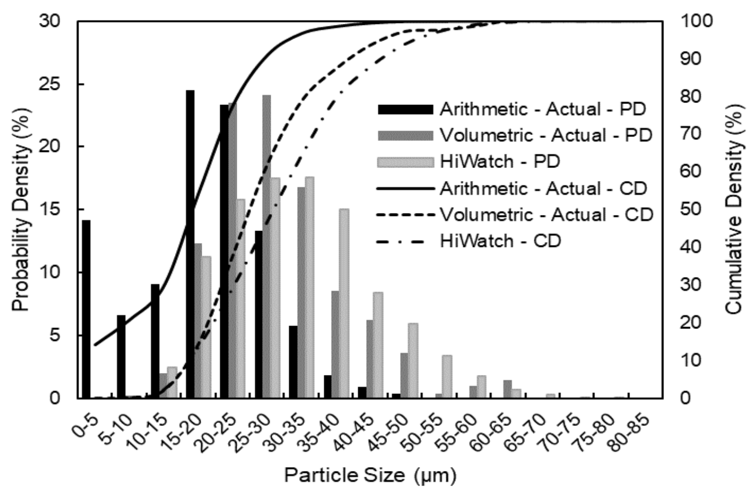
VRC System
Nozzle 71
Nitrogen
65 bar, 425 C
Mil Spec Al6061 Powder
Valimet

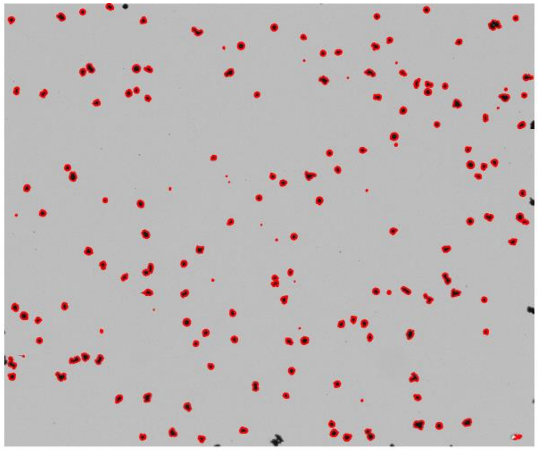




Transmission Microscopy
Valimet-MilSpec-Al6061

SPEE3D System
Water Cooled Nozzle
Air
35 bar, 500 C
Copper Powder
Praxair





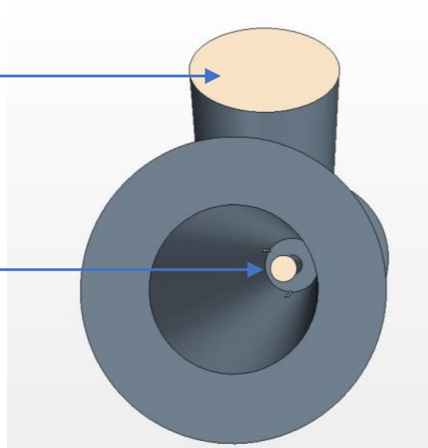
Transmission Microscopy
Praxair Cu-159-3

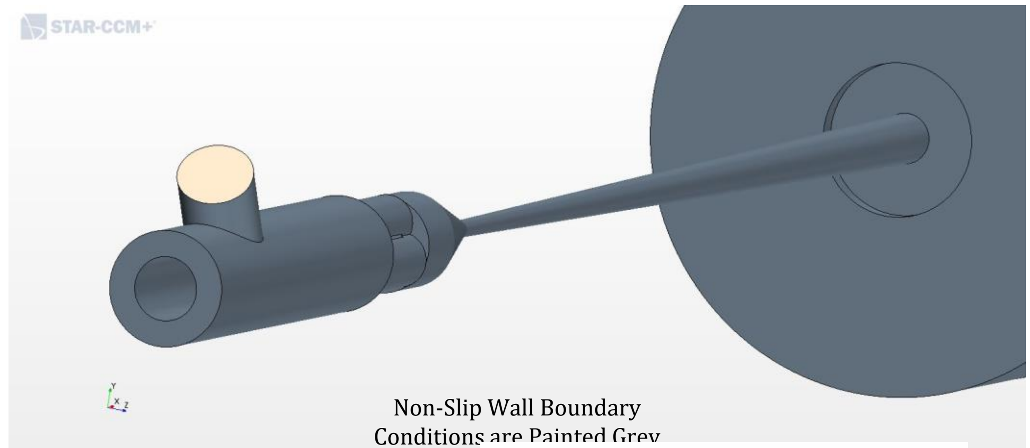
3D CFD Model Domain Boundaries

Particle Flight Behavior & Impact Velocity and Temperature

Hot Gas
Mass Flow Inlet

Cold Gas/Powder
Mass Flow Inlet

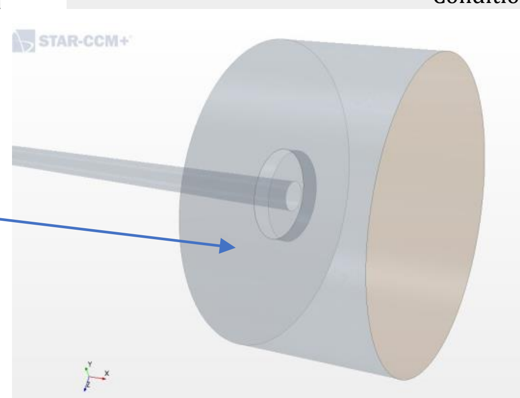




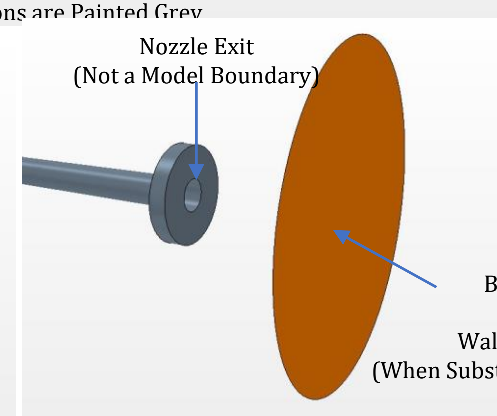
Non-Slip Wall Boundary
Conditions are Painted Grey

Wall Boundary
or
Outlet Boundary
(When Substrate is Considered)

This boundary is setup as a non-slip wall boundary condition to help stability when computational power is limited and mesh is course.



Nozzle Exit
(Not a Model Boundary)



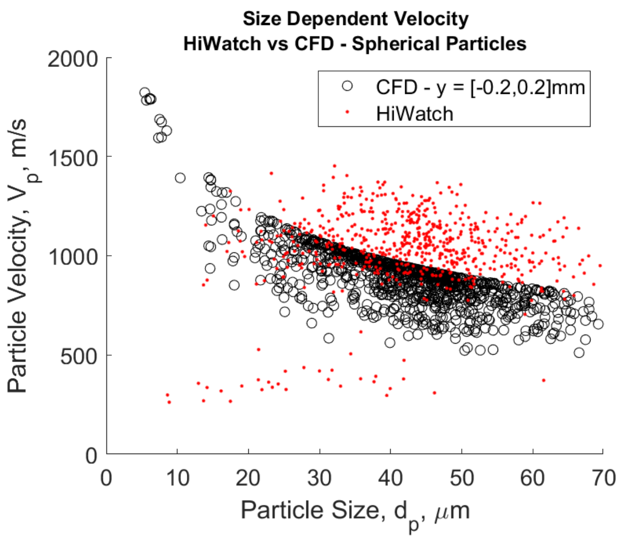
Outlet
Boundary
or
Wall Boundary
(When Substrate is Considered)

Continuous Phase Computations

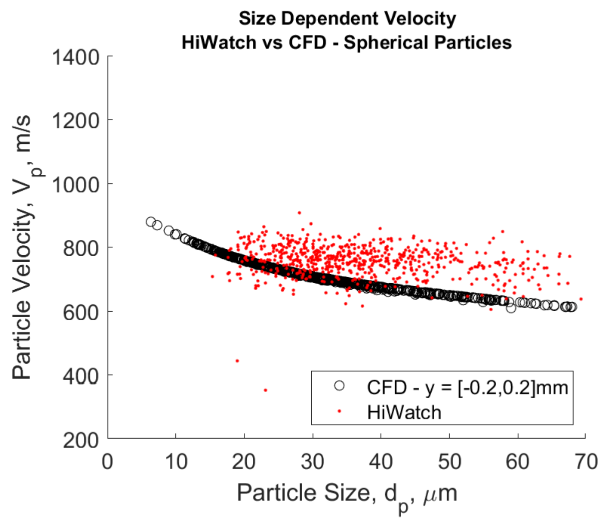
- Navier Stokes Equations of Mass, Momentum, and Energy Conservation
- Realizable k-ω Shear Stress Transport Reynolds Averaged Navier Stokes Approximation

Initial HiWatch vs CFD Comparisons

Particle Flight Behavior & Impact Velocity and Temperature



VRC System
Nozzle 71
Helium
35 bar, 425 C
Mil Spec Al6061 Powder
Valimet



VRC System
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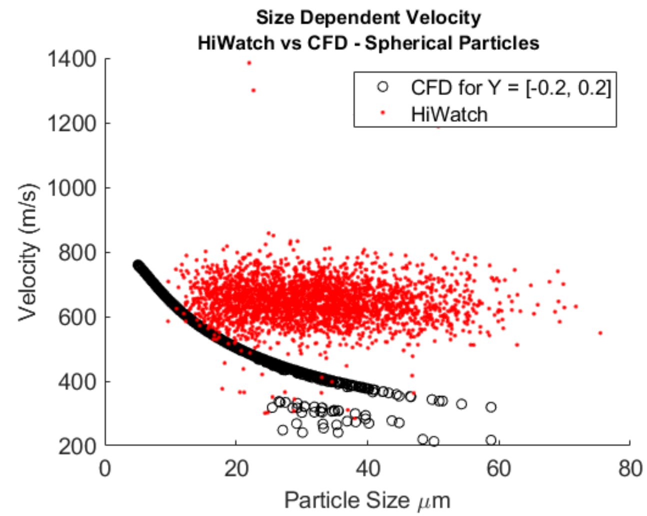
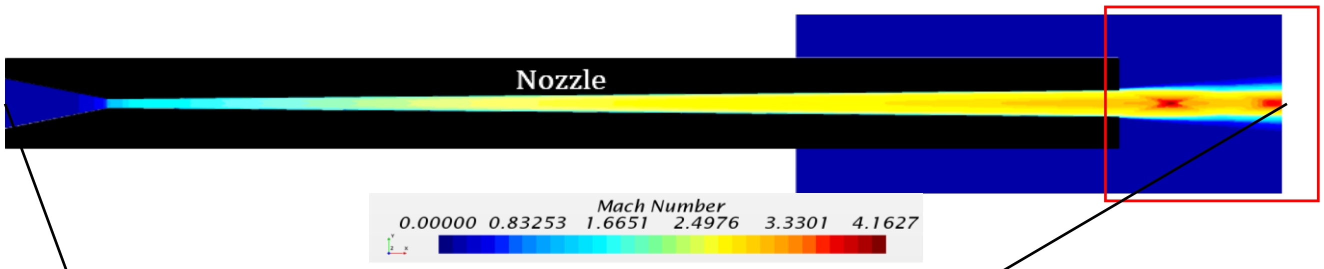


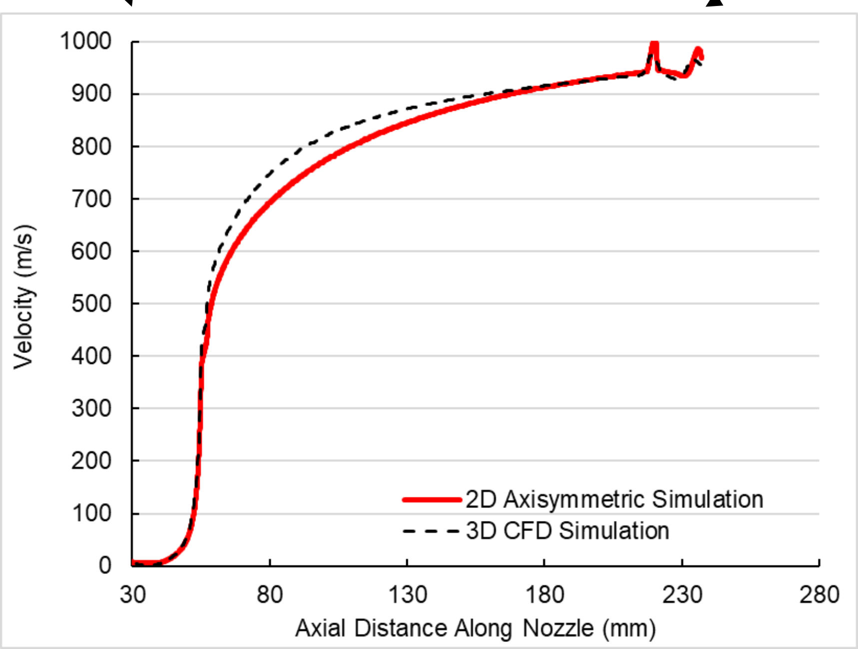
SPEE3D System
Water Cooled Nozzle
Air
35 bar, 500 C
Copper Powder
Praxair

- Mean particle velocity measurements with full particle size distribution (PSD) match mean measurements by HiWatch
- But HiWatch PSD does not match with actual powder PSD
- CFD simulations carried out by HiWatch measured PSD show discrepancy in mean and size dependent particle velocity.
- Possible causes
  - HW measures size inaccurately (ruled out after discussions with manufacturer)
  - Gas dynamics is not captured properly
  - Particle dynamics is not captured properly

Confirmation of Gas Dynamics Calculations through Schlieren Imaging

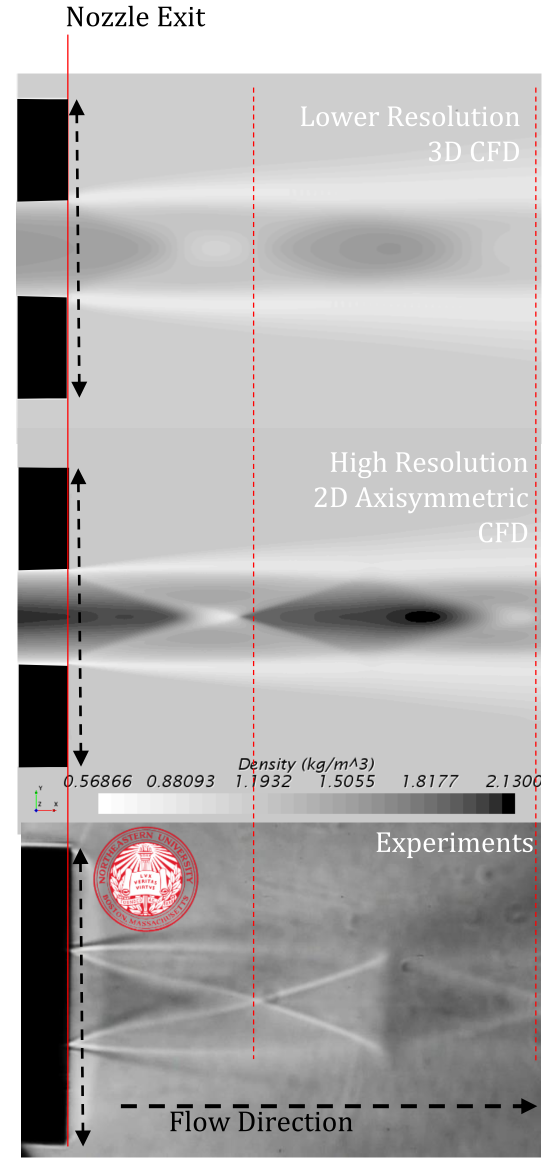
Evaluate & Refine





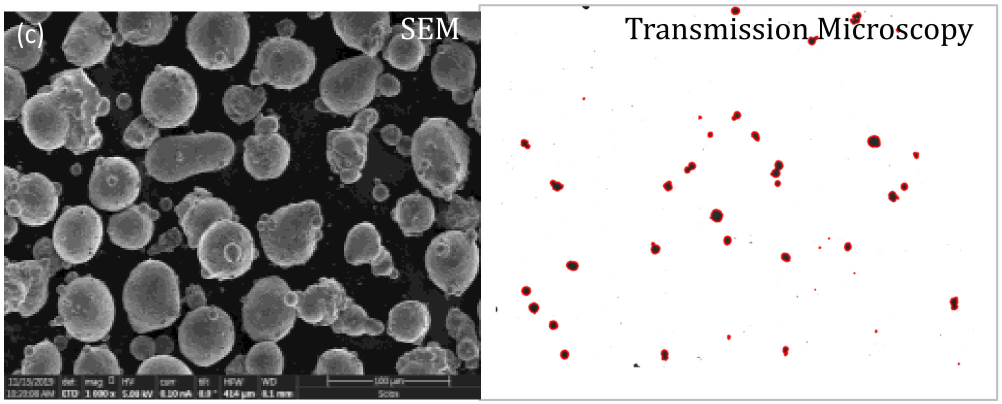
VRC System
Nozzle 71
Nitrogen
65 bar, 425 C
Mil Spec Al6061 Powder
Valimet

- Schlieren image of the nitrogen case shows that the supersonic jet formation is captured accurately by 2D axisymmetric CFD.
- Hi resolution 2D Axisymmetric simulation matches well with the lower resolution 3D simulations.
- Slight differences are expected.
- Mismatch is not sufficiently high to justify the big difference in particle velocity.



How spherical are gas atomized particles?

Evaluate & Refine



gas atomized aluminum particles

Drag Coefficient of Off-Spherical Particles

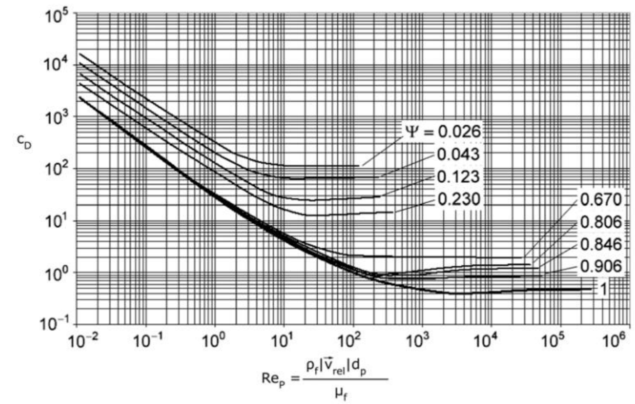


Figure 4.5. Drag coefficient of a non-spherical particle dependent on the particle Reynolds number and the sphericity ψ.

S. Martin, J.R. Williams, Multiphase Flow Research, Nova Science Publishers, Inc., 2009

$$\Psi = \frac{Surface\ Area\ of\ Equivalent\ Volume\ Sphere}{Surface\ Area\ of\ Particle}$$

$$C_D = \frac{24}{\mathrm{Re}_p}\left[1 + \exp\left(2.3288 - 6.4581\Psi + 2.4486\Psi^2\right)\cdot \mathrm{Re}_p^{(0.0964+0.5565\Psi)}\right] + \frac{\exp\left(4.905 - 13.8944\Psi + 18.4222\Psi^2 - 10.2599\Psi^3\right)\cdot \mathrm{Re}_p}{\exp\left(1.4681 + 12.2584\Psi - 20.7322\Psi^2 + 15.8855\Psi^3\right) + \mathrm{Re}_p}$$

S. A. Morsi and A. J. Alexander, "An investigation of particle trajectories in two-phase flow systems," *J. Fluid Mech.*, vol. 55, no. 2, pp. 193-208, 1972, doi: 10.1017/S0022112072001806.

$$\Psi = d_n/a$$
$$\Psi = (bc/a^2)^{\frac{1}{3}}$$
$$\Psi = c/(ab)^{\frac{1}{2}}$$
$$\Psi = (c^2/ab)^{\frac{1}{3}}$$

$\Psi = sphericity$
$d_n = nominal\ diameter$
$a = major\ axis$
$b = median\ axis$
$c = minor\ axis$

Cold spray Re_p range: $0 < \mathrm{Re}_p < \sim 10^3$
Significant effects of shape on velocity expected.

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Powder Characterization

Particle shape distribution for Al and Cu through transmission microscopy.

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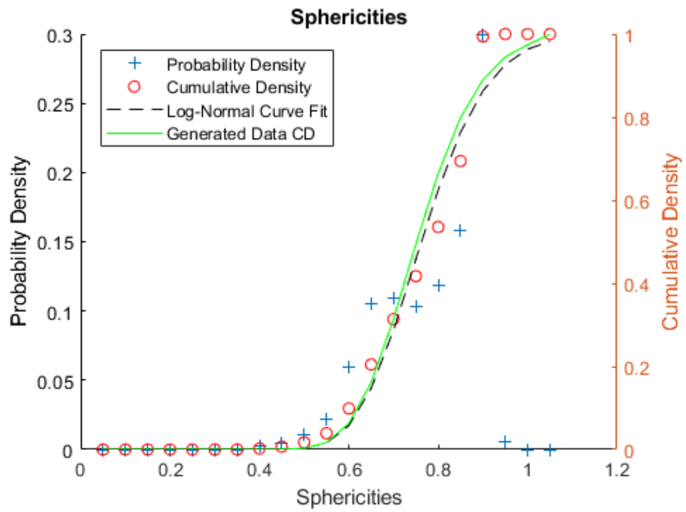
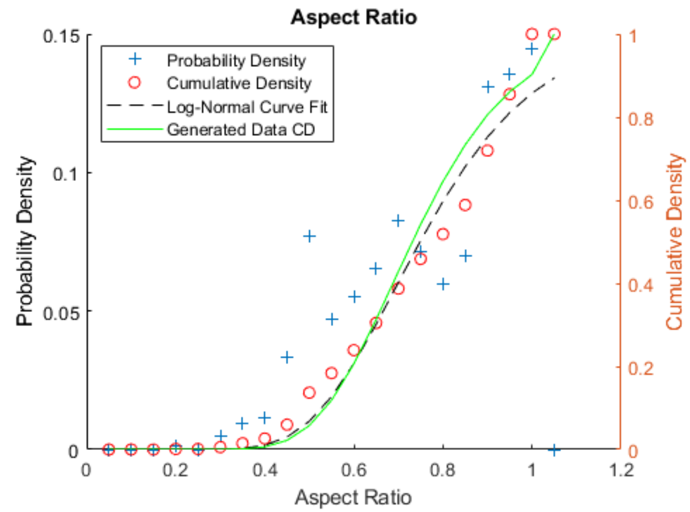
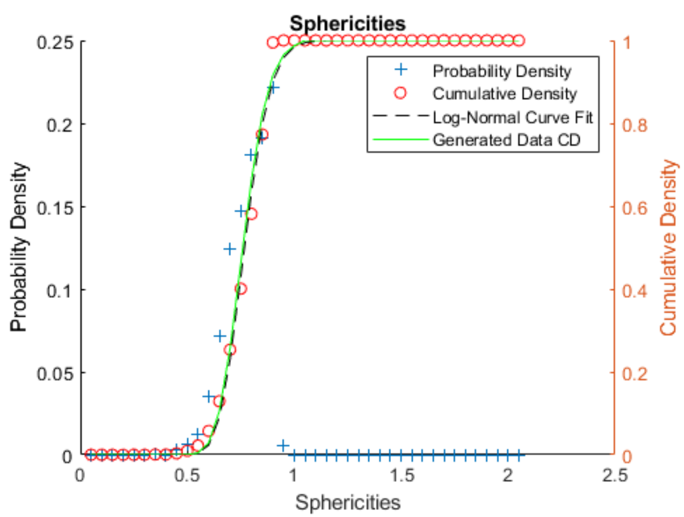
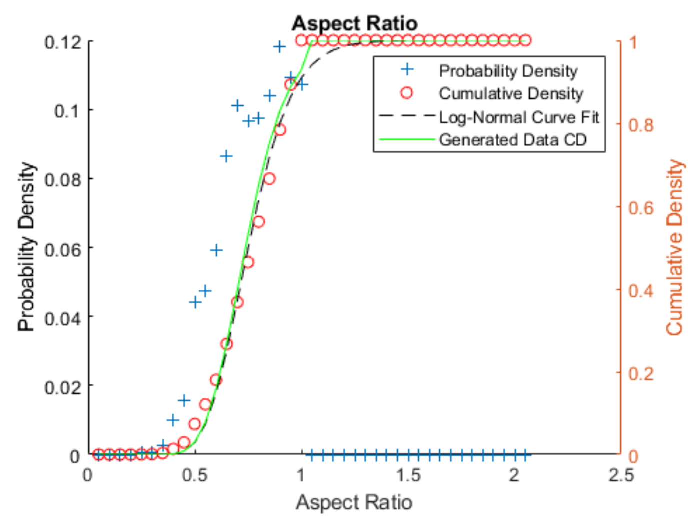




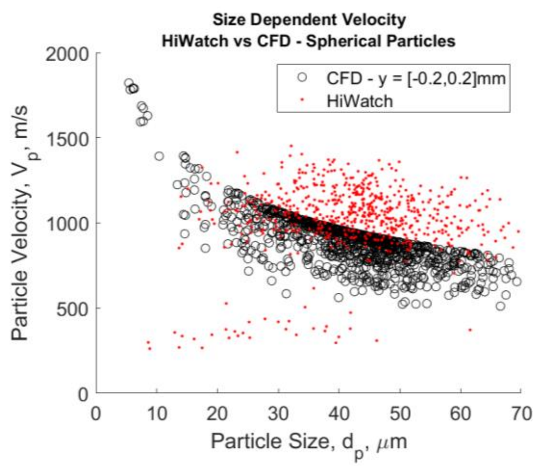
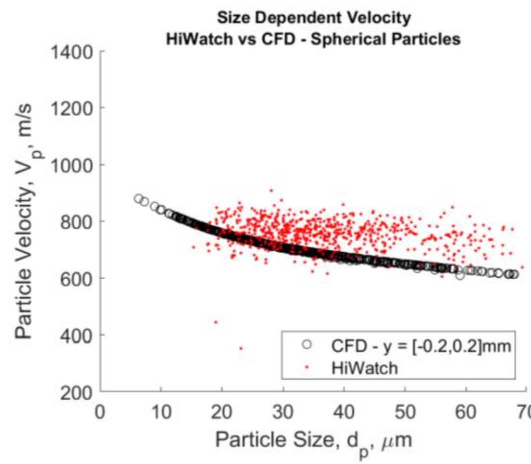
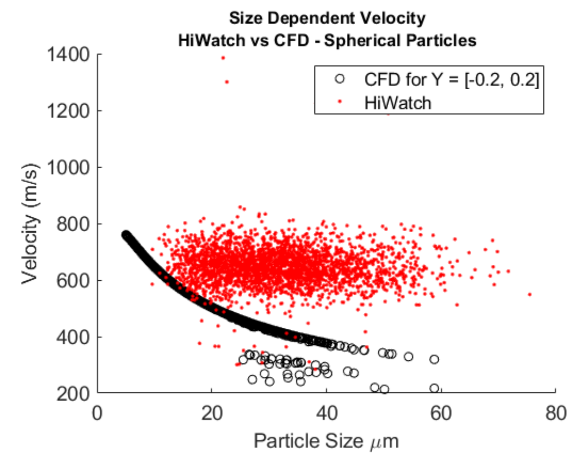
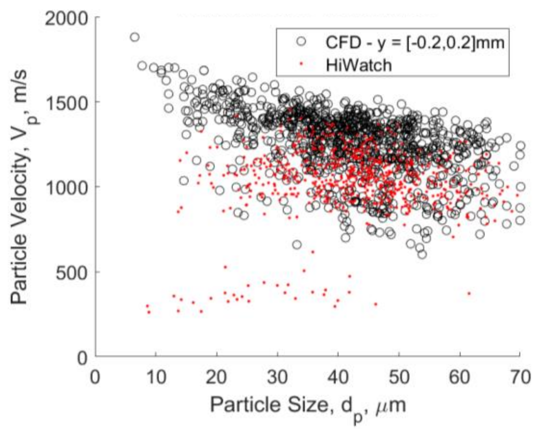
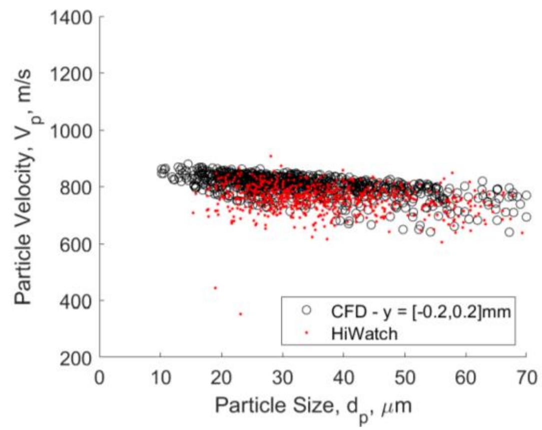
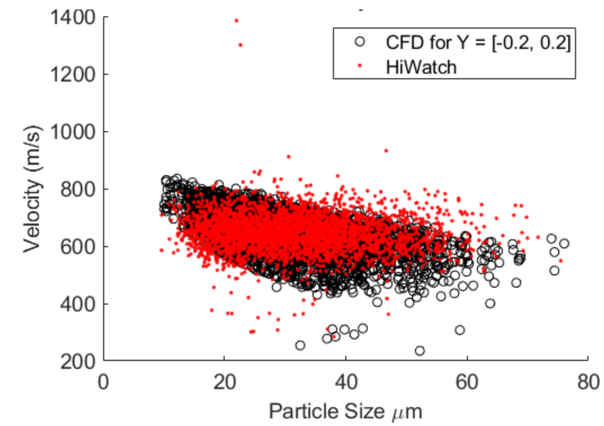
SPEE3D System
Water Cooled Nozzle
Air
35 bar, 500 C
Copper Powder
Praxair Cu-159-3





Effects of Sphericity

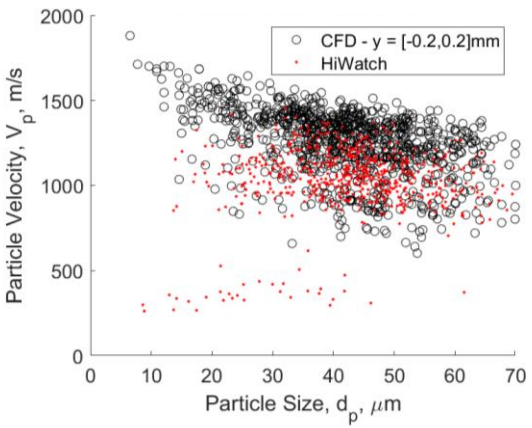
Particle Flight Behavior &
Impact Velocity and
Temperature

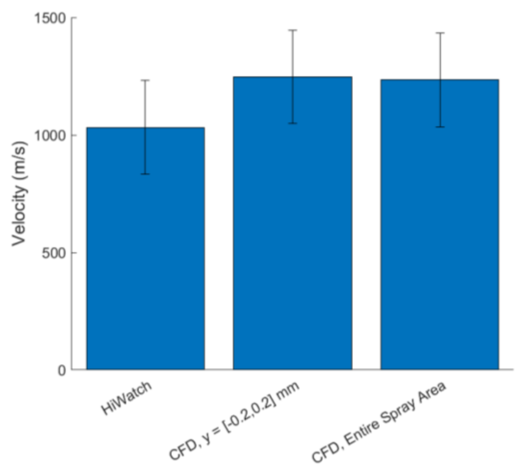
	VRC System Nozzle 71 Helium 35 bar, 425 C Mil Spec Al6061 Powder	VRC System Nozzle 71 Nitrogen 65 bar, 425 C Mil Spec Al6061 Powder	SPEE3D System Water Cooled Nozzle Air 35 bar, 500 C Praxair Copper Powder
Perfectly Spherical Particles			
Variable Sphericity Particles			

Velocity Estimation

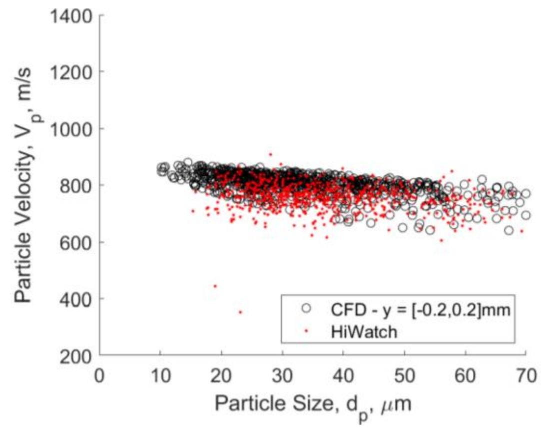
Particle Flight Behavior & Impact Velocity and Temperature

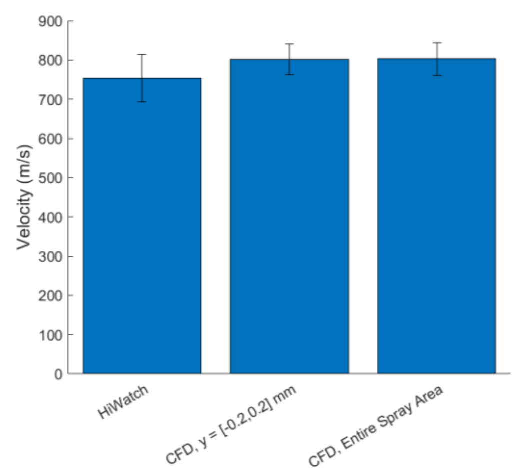
VRC System
Nozzle 71
Helium
35 bar, 425 C
Mil Spec Al6061 Powder



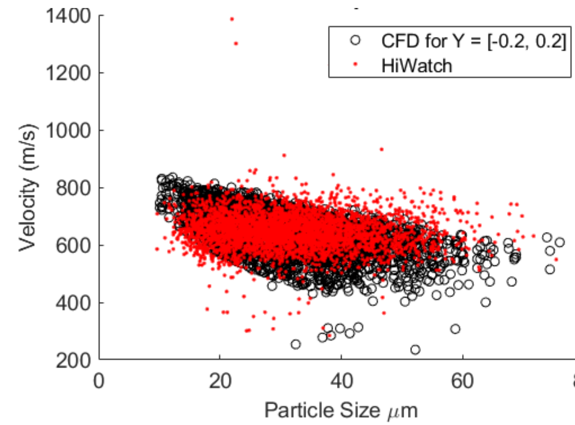


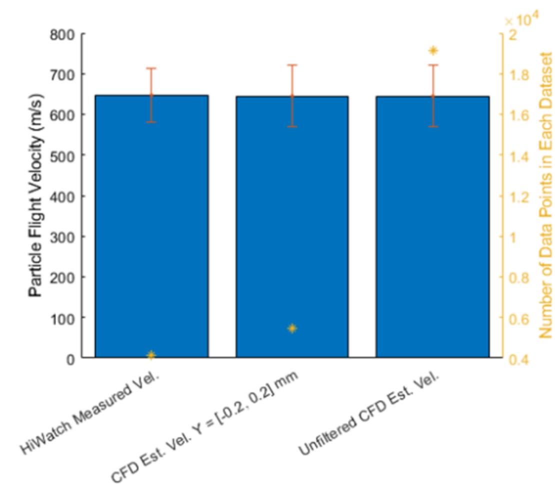
VRC System
Nozzle 71
Nitrogen
65 bar, 425 C
Mil Spec Al6061 Powder





SPEE3D System
Water Cooled Nozzle
Air
35 bar, 500 C
Praxair Copper Powder





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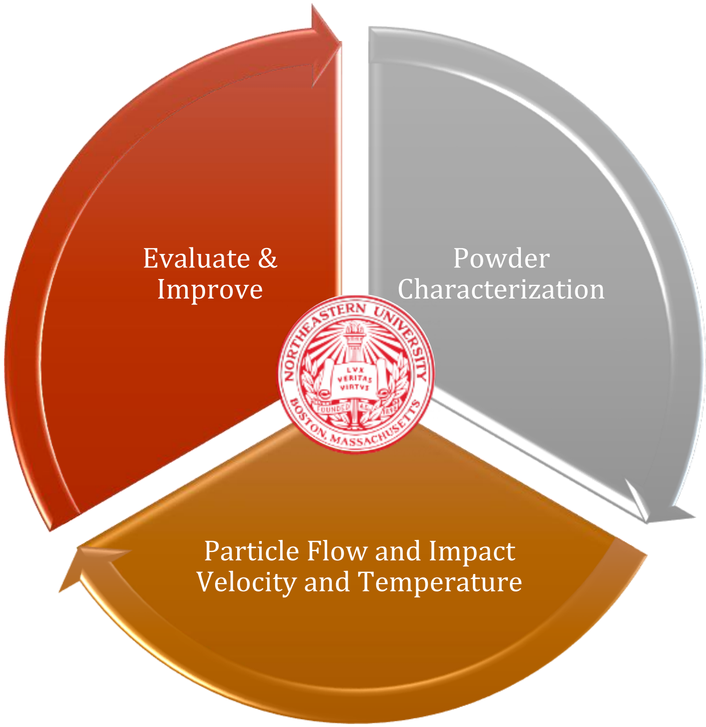
Refine Particle Shape Measurement



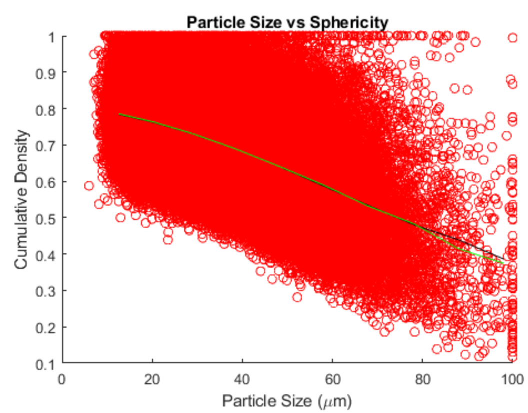
Refined particle shape analysis through measurement of 3rd dimension through interferometry

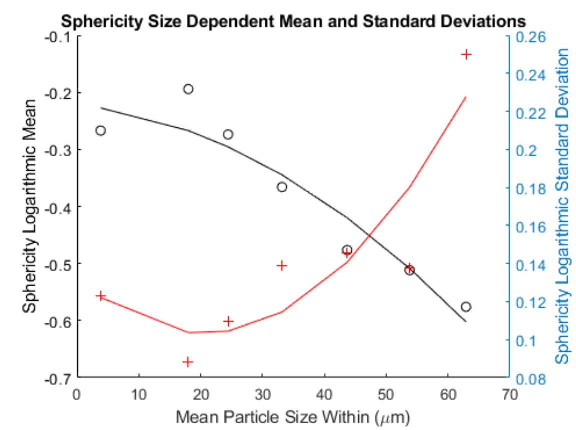
$$\Psi = \frac{Surface\ Area\ of\ Equivalent\ Volume\ Sphere}{Surface\ Area\ of\ Particle}$$

$$\Psi = d_n/a$$
$$\Psi = (bc/a^2)^{\frac{1}{3}}$$
$$\Psi = c/(ab)^{\frac{1}{2}}$$
$$\Psi = (c^2/ab)^{\frac{1}{3}}$$

$\Psi = sphericity$
$d_n = nominal\ diameter$
$a = major\ axis$
$b = median\ axis$
$c = minor\ axis$

Dependency of particle shape to particle size.

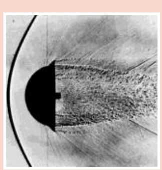




Major Findings

Particle shape, generally not measured in cold spray, is an important factor for impact velocity.

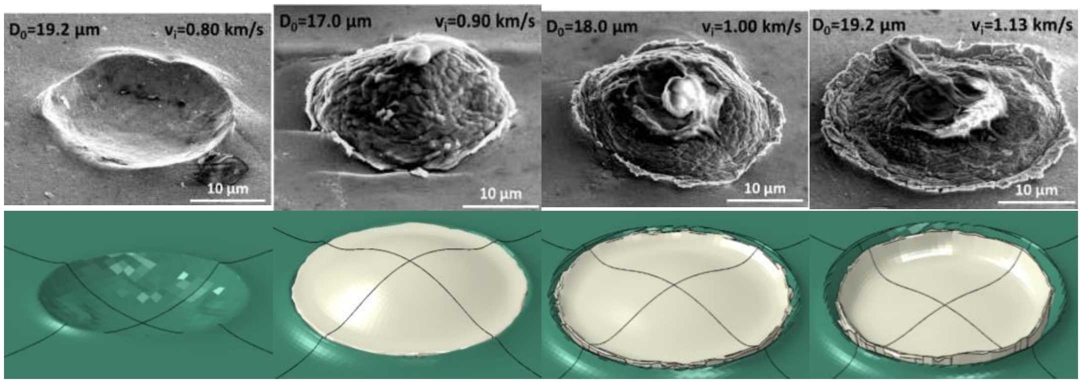
Particle shape measurement methods developed throughout this study needs to be improved to increase accuracy.



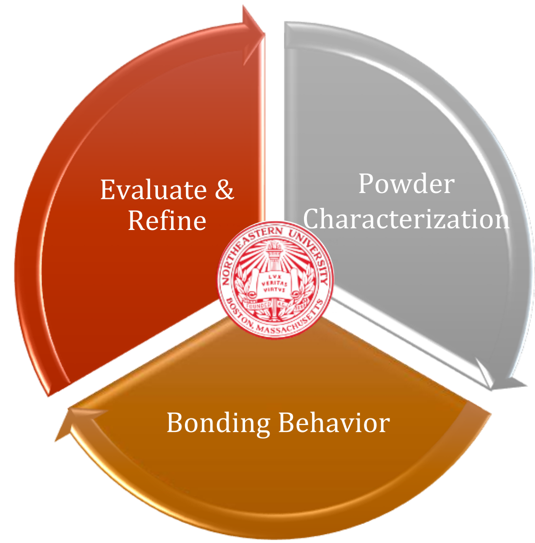
Bow shock that forms ahead of the substrate has a significant impact on particles that have off-spherical shapes. (More thorough analysis of this work will be published.)

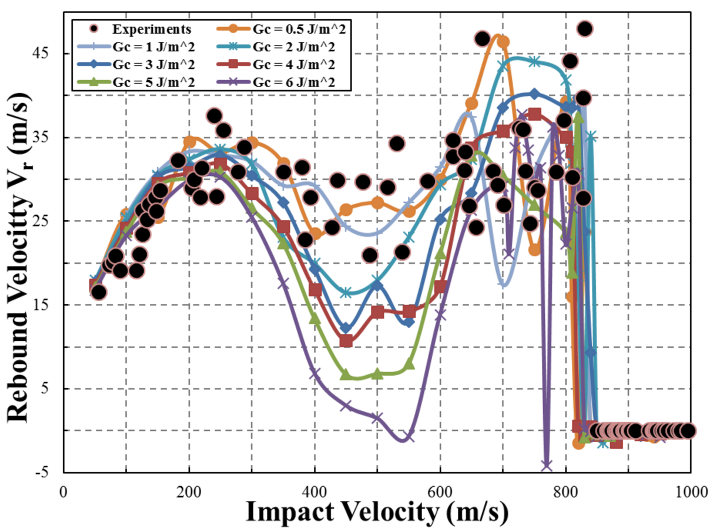
Calibrated Models Provide Interfacial Energy and Thermal Energy Rise During Impact

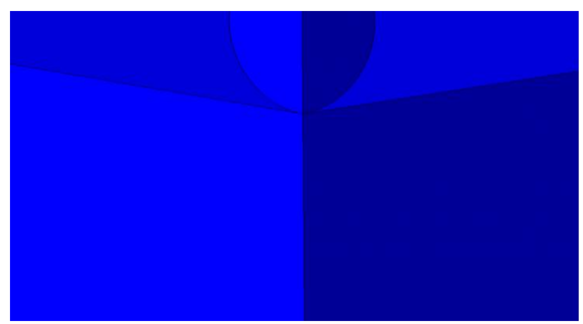
W. Xie, J.-H. Lee, UMASS



Q. Chen, et al., NU







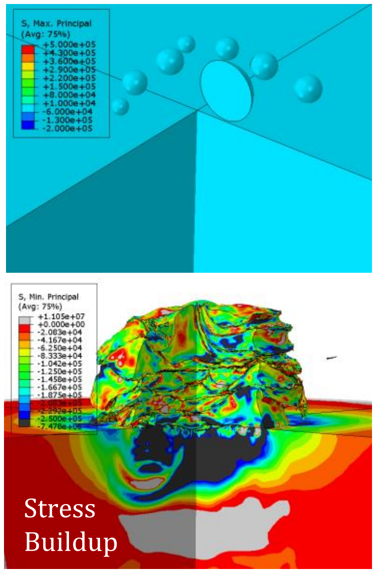
$V_c = 884$ m/s
$G^{Al} = 25$ J/m^2

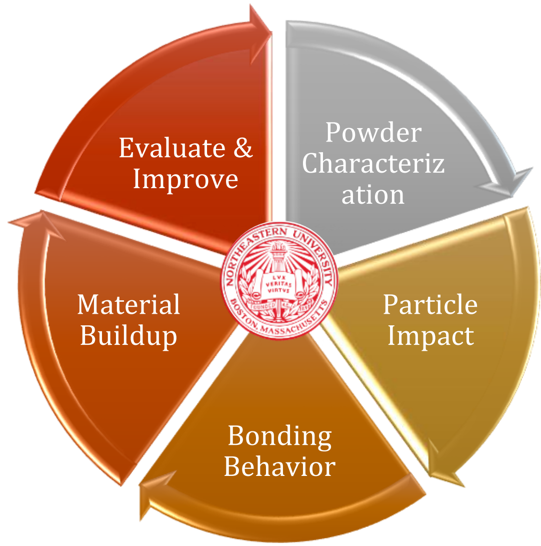
Thermal energy conversion to kinetic energy

$$TE_{particle} = 0.34 \cdot KE$$

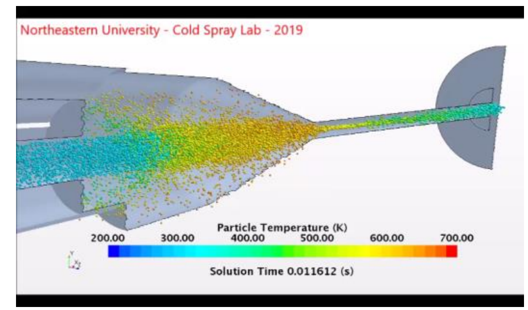
$$TE_{substrate} = 0.45 \cdot KE$$

Building on findings

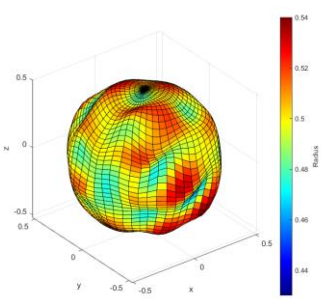


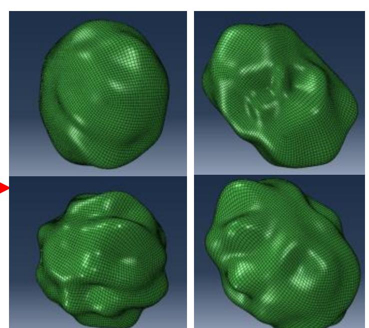


Refined particle shape analysis through measurement of 3[rd] dimension by interferometry

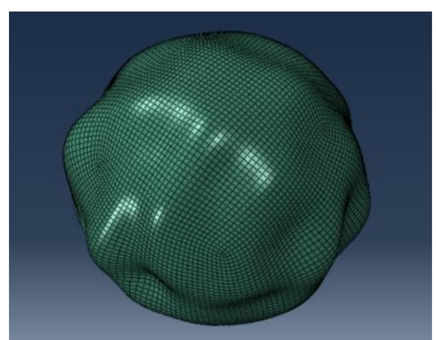


Shape Dependent Behavior



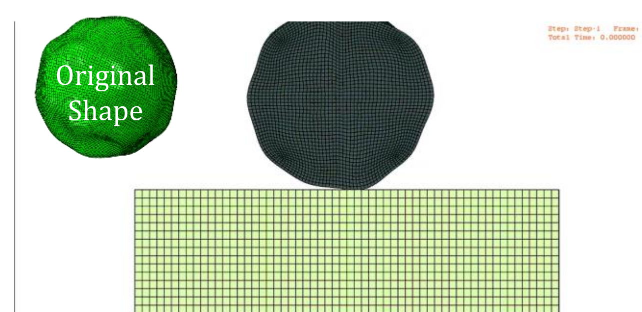


Script to generate parametrized shapes



Import into FEM Models

Sample impact FEM: Al-6061, 22 μm, 636 m/s



Thank you!
Questions

Acknowledgements

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