Cold Spray Modeling

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Sandia National Laboratories

Analytical Project Goals

Development of an understanding of the process

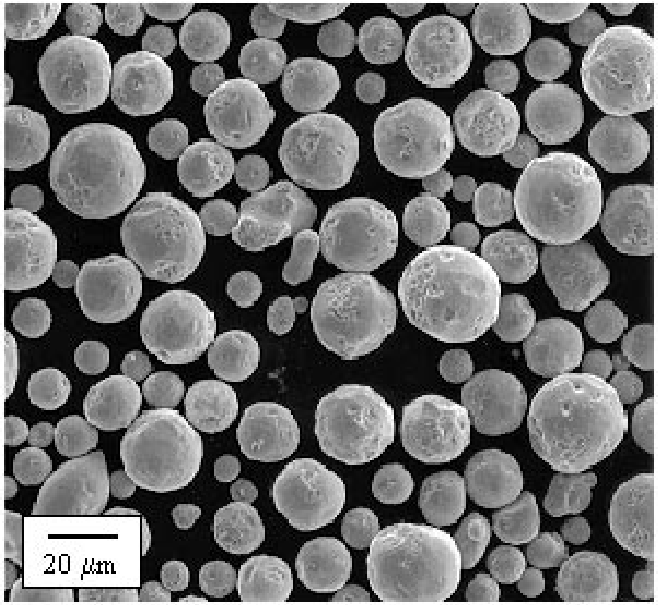
- **Particle acceleration**
- **Particle impact**
- **Coating buildup**

Optimization

- **Process costs**
    - **gas and powder usage**
    - **coating times**
- **Coating properties**
    - **adhesion**
    - **porosity**

Statistical Process

- **Powder feed**
  - **powder size variation**
  - **powder shape variation**
  - **powder porosity variation**
  - **powder chemistry (phase content)**
- **Gas Stream**
  - **Gas velocity variation**
  - **Gas chemistry variation (3 gas streams)**
- **Trajectory**



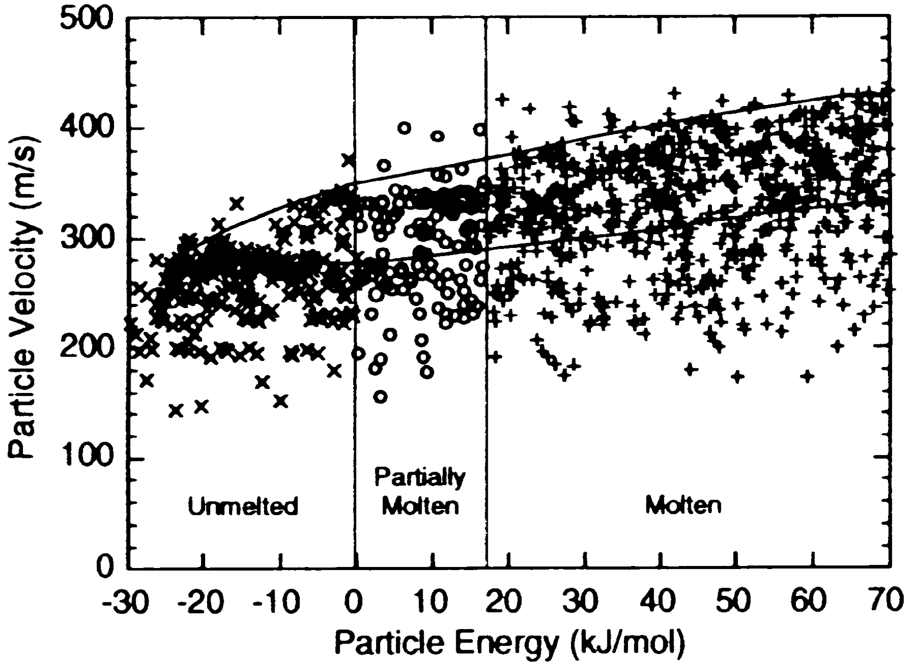
Variations result in changing impact orientations, velocities, and angles. Goal is to design a robust process so that these variations do not reduce the coating quality.

Thermal Spray Optimization

- **Goal: Determination of spray parameters that will result in all spray particles impacting substrate with optimal velocity and thermal energy.**
  - **Want them molten, but not too hot**
  - **Want them traveling fast but not too fast**
- **Method:**
  - **Develop a numerical model for the spray processes**
  - **Find spray settings (chamber pressure, thermal power, gas flow rate, standoff, He/Ar mixture) that yield optimal impact conditions**
  - **Find spray settings that are insensitive to powder size**

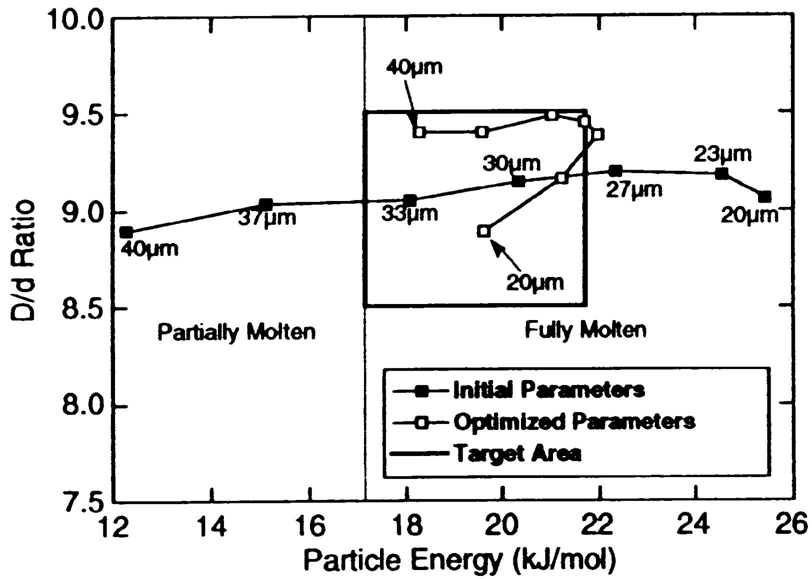
3125 input parameter combinations

By varying input parameters (gas flow, gas composition, particle size, electric power, etc.) almost any impact condition can be obtained:



Sensitivity to Particle size

- One "Optimal" condition only works for 30 and 33 micron particles
- Another works for all particles from 20 to 40 microns
- Found automatically by creating an output function that gives points for each size hitting target



Cold Spray
Impact Simulation

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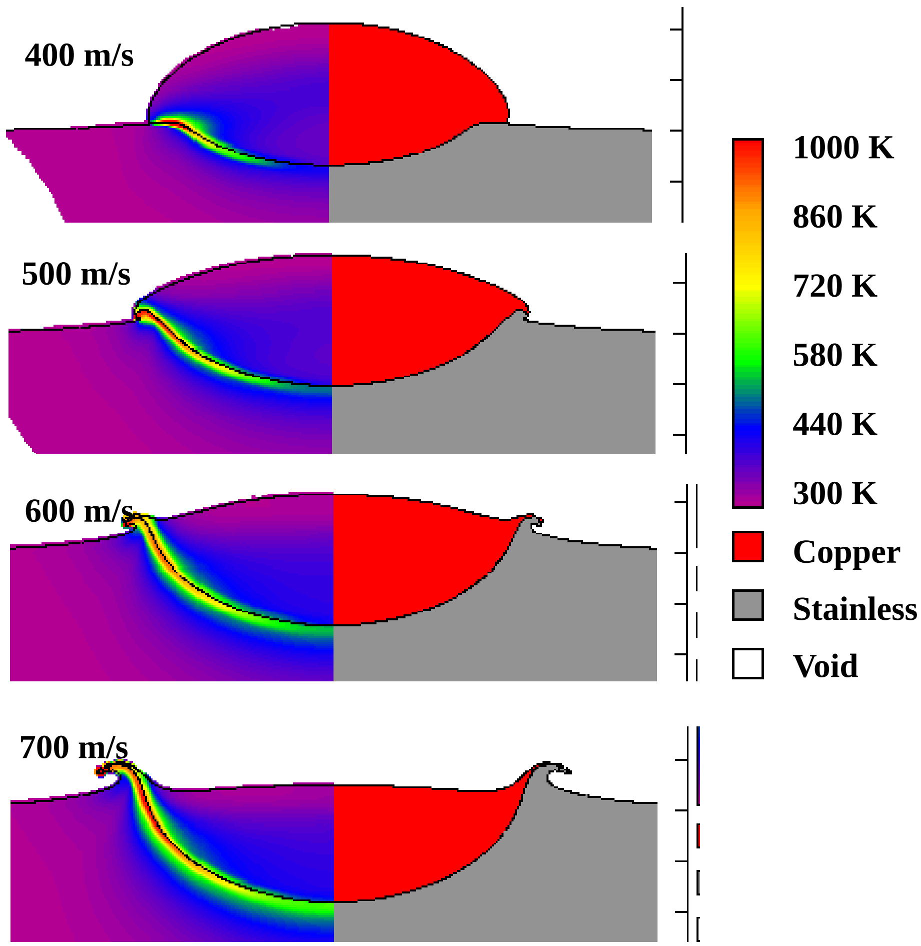

Higher velocities result in more penetration into the substrate and more particle deformation

Higher velocities result in higher temperatures, but still below melting

Transient Simulation Results
(Potential JTST cover art)

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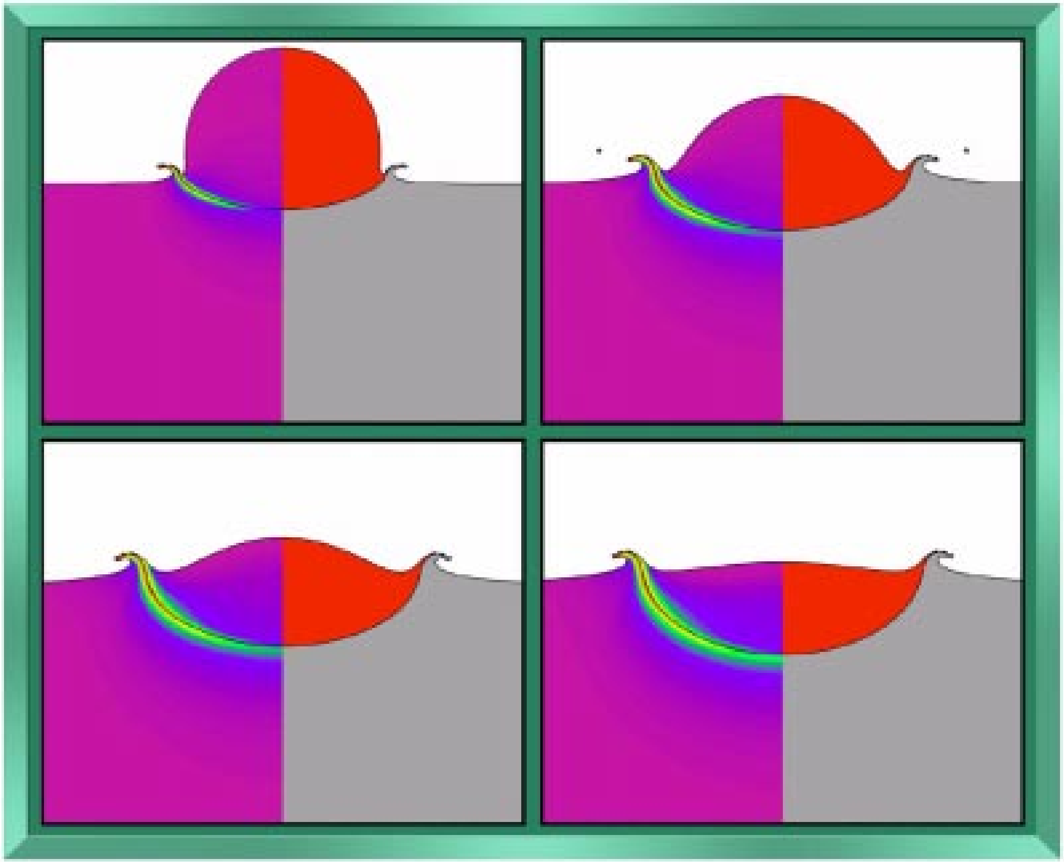
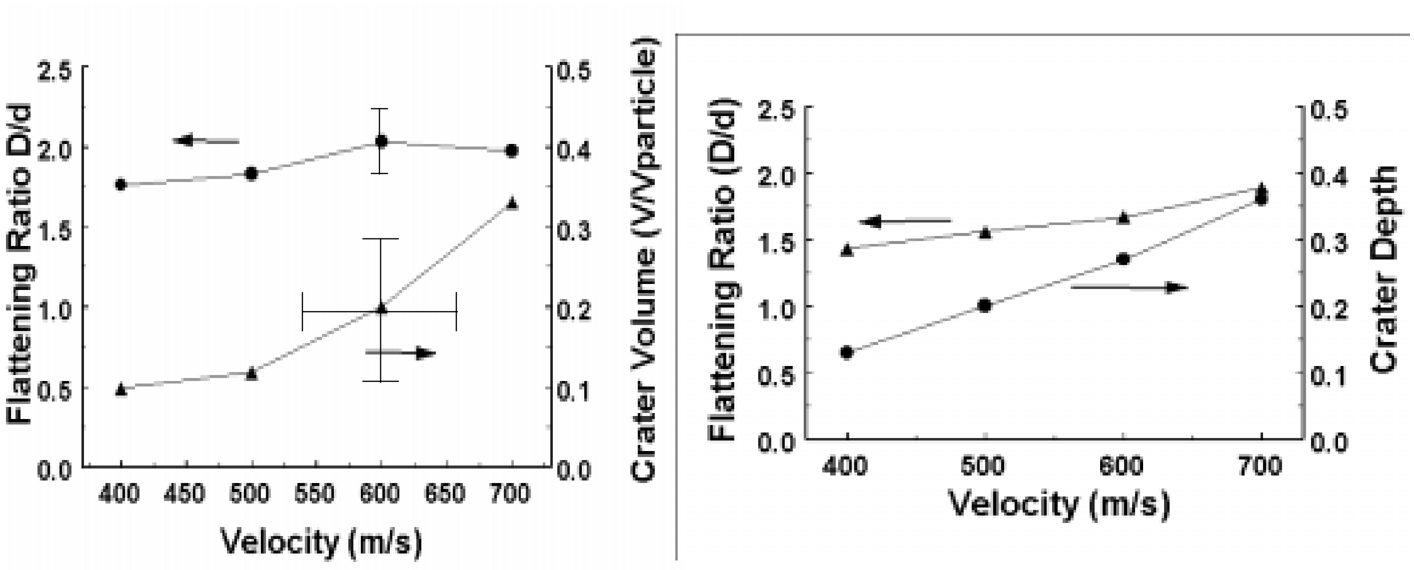


movie: http://sherpa.sandia.gov/9231home/papers-frame.html

Experiments and Modeling Correlate Well



Experimental **Calculated**

- **Lots of scatter in the experimental due to various particle sizes and velocities within an experiment.**
- **Calculated allows examination of trends without these variations**

Cold Spray
Optimal Nozzle Shape

- **Nozzle design is an area of interest in many applications**
- **Engine - Optimize thrust**
- **Wind Tunnel - Optimize gas velocity uniformity**
- **Cold Spray - Optimize particle velocity**
  - **Fastest particle velocity does not demand simply the fastest gas velocity**

    small particles
    long nozzles
    high density gas
    high velocity gas
    high specific heat ratio gas

Analytical Model of Cold Spray

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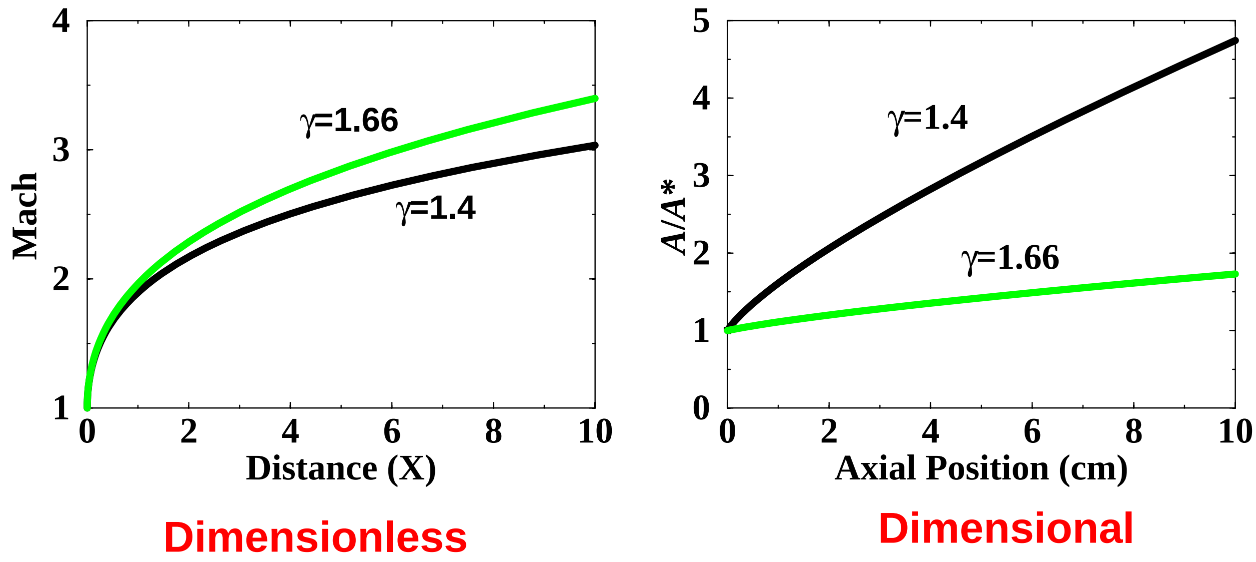
Unlike Thermal Spray which often include chemical reactions, cold spray can be modeled analytically:

$$\frac{dM}{dX}\left(\frac{2+(\gamma-1)M}{2+(\gamma-1)M^2}\right)(M-1) = \left(\frac{2+(\gamma-1)M^2}{2}\right)^{\frac{-1}{\gamma-1}}$$

$$X = \frac{xC_D A_p \rho_o}{2m} \qquad \frac{A}{A^*} = \left(\frac{1}{M}\right)\left(\left(\frac{2}{\gamma+1}\right)\left(1+\frac{\gamma-1}{2}M^2\right)\right)^{\frac{\gamma+1}{2(\gamma-1)}}$$

The above equation is integrated numerically to yield nozzle shape for maximum acceleration

Solve Equation for Area as a function of Nozzle Length



Results show that an optimal helium nozzle is much different than an optimal air nozzle

However, the results show that the optimal nozzle is not significantly better than non-optimal designs as long as reasonable design rules are followed.

Analytical Cold Spray Velocities Comparison to Experiments

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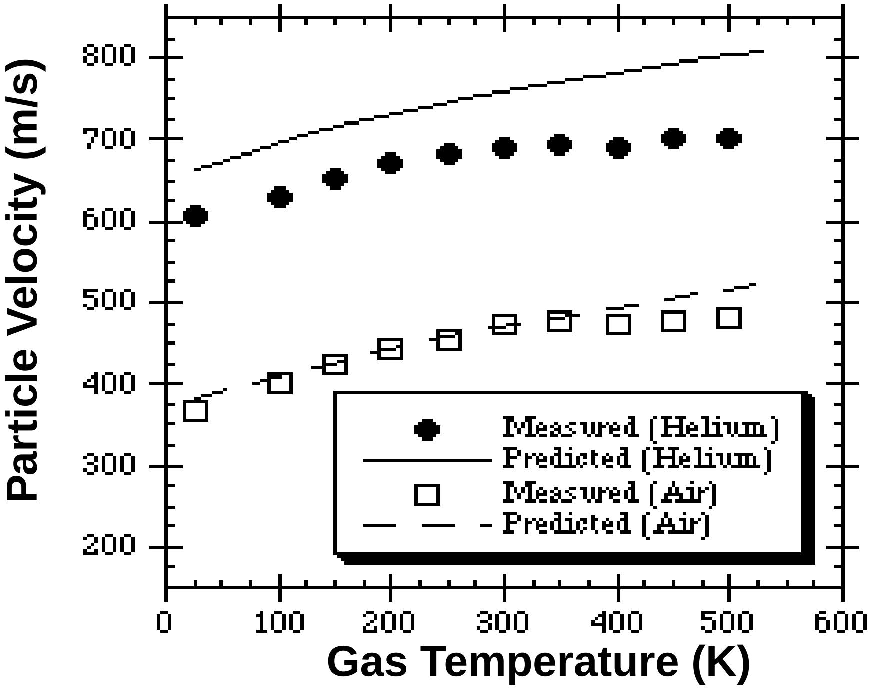
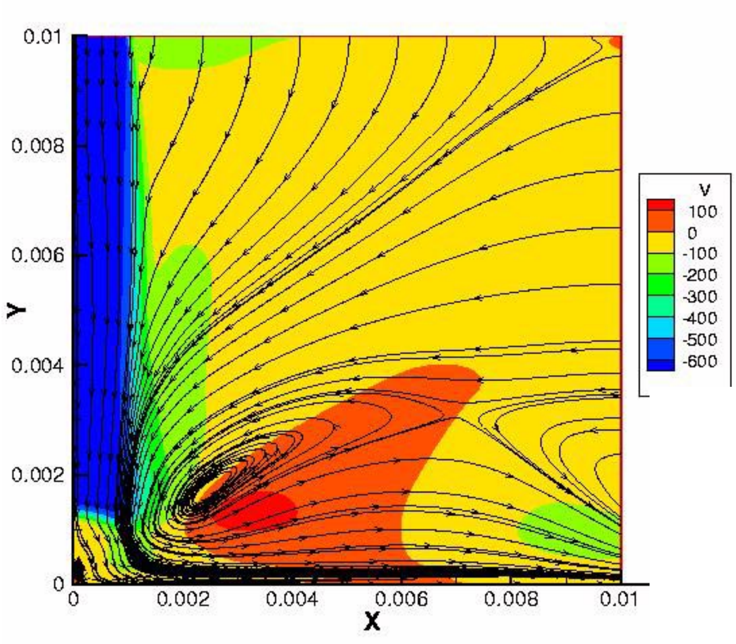
Analytical result shows that particle velocity increases with gas temperature

Experiments do not show monotonically increasing particle velocity with increasing temperature

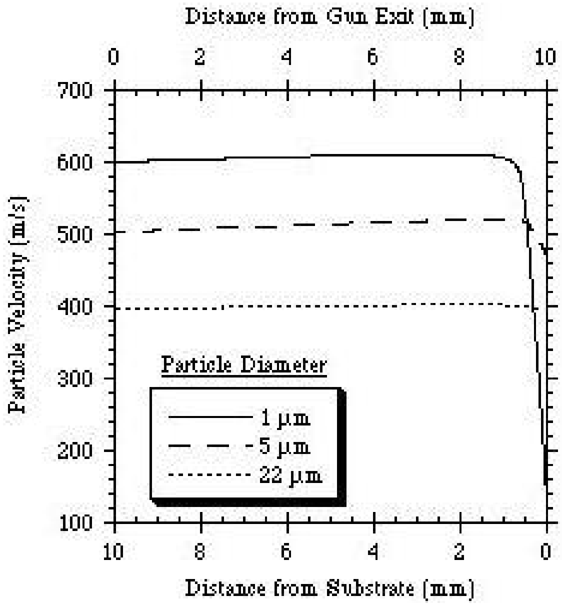


Two-dimensional Cold Spray Jet Impact (gas velocities and streamlines)

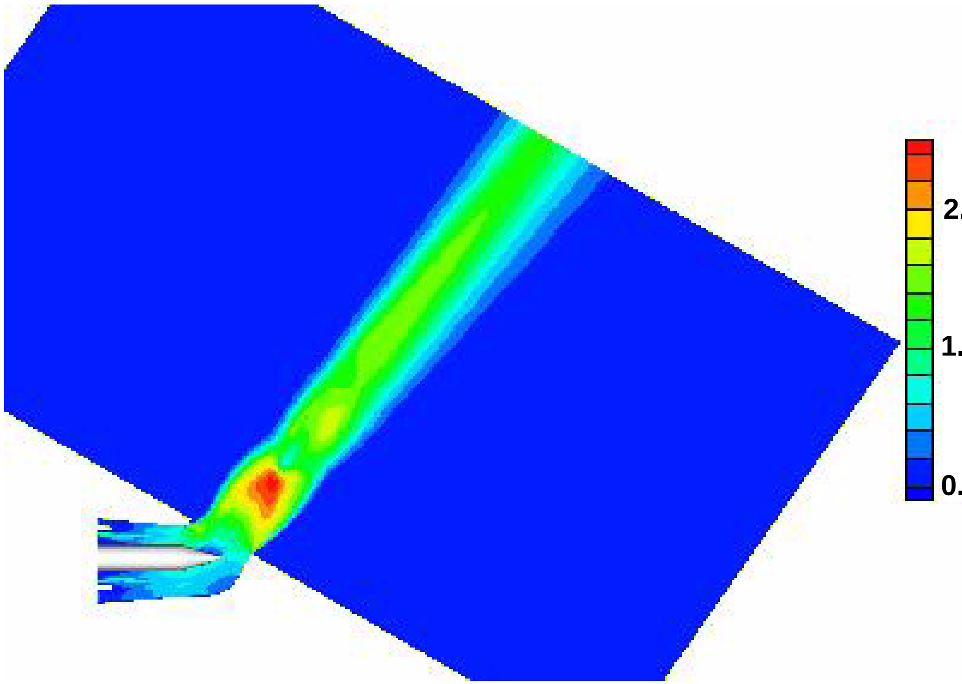


We obtain particle trajectories from this output

This was done to determine actual particle impact velocities on a substrate due to low gas velocities at substrate



Three dimensional HVOF Calculations



Mach Number distribution from a wire fed HVOF nozzle

Summary

- **Modeling aids our understanding of spray processes**
  - **particle trajectories and acceleration**
  - **chemical reactions**
  - **droplet breakup**
  - **particle impact**
- **Modeling allows easier examination of process trends**
  - **experiments are forced to examine ensemble averages**
- **Modeling allows easier optimization**
  - **modeling can point to operational points that have not been examined**
- **Modeling must be supported by experimental efforts**
  - **modeling is only an approximation of reality**