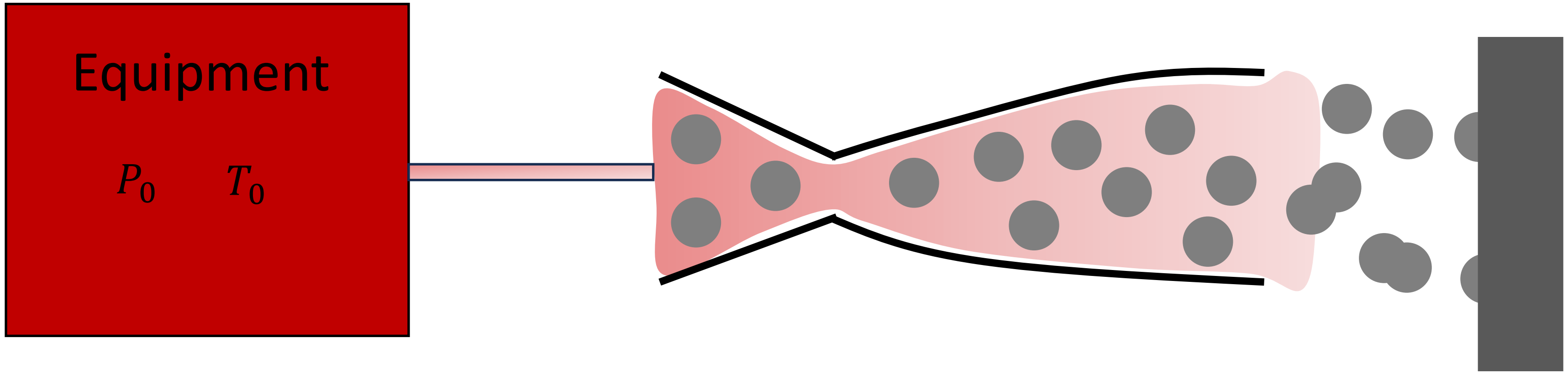
Durability and Mechanical Integrity of Structural Materials
The Cold Spray Club

An analytical methodology to determine the equipment requirements for adhesion in cold spray



Authors:

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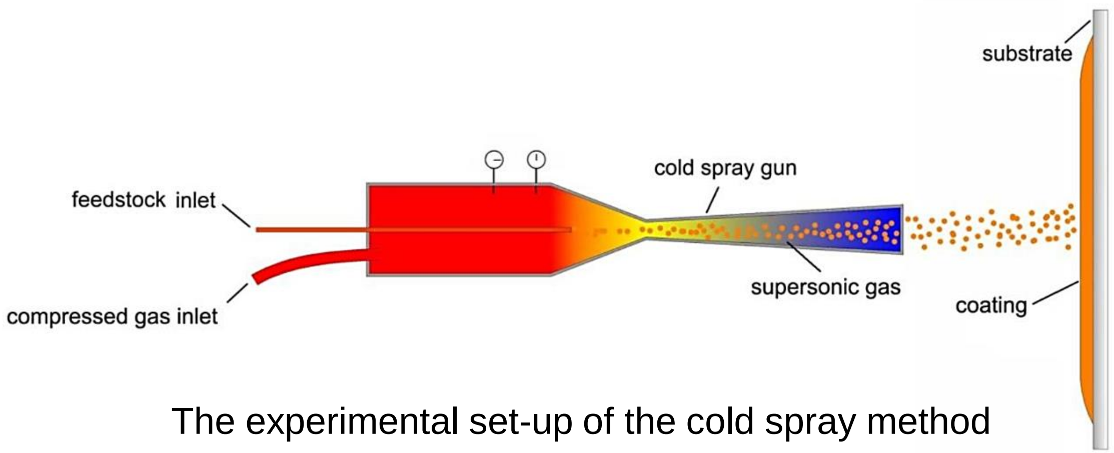
Hamburg, October 20th , 2023

Understanding the inputs to select the equipment



The experimental set-up of the cold spray method

Applications

- Reparation of components
- Additive manufacturing

Reparation of a crack

Additive manufacturing of a rocket nozzle

How do we know the necessary equipment to achieve adhesion?

What are the stagnation conditions to use?

Inputs needed

- Critical velocity
- Characteristics of the powder and gas
- Nozzle geometry

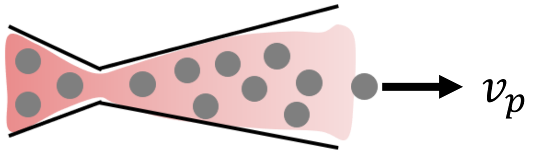
→ **Equipment** → **Stagnation conditions**

Analytical model offering multiple possibilities

- Model based on the one-dimensional isentropic theory
- Analysis of the dynamics of the dilute two-phase flow

Model

Predictive tool

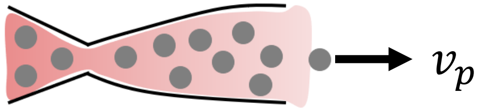


Known geometry

- Stagnation conditions
- Powder characteristics
- Nozzle geometry
- Carrier gas

→ Exit particle velocity

Optimization tool



Optimal geometry

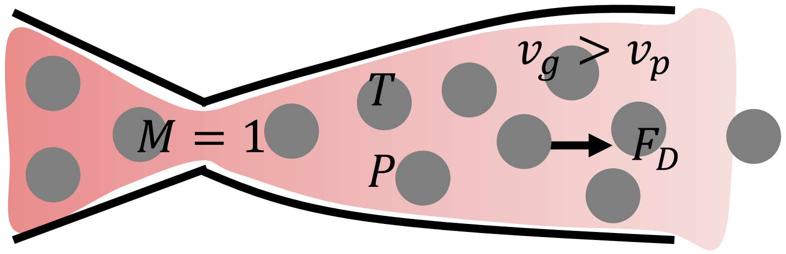
- Stagnation conditions
- Powder characteristics
- Carrier gas

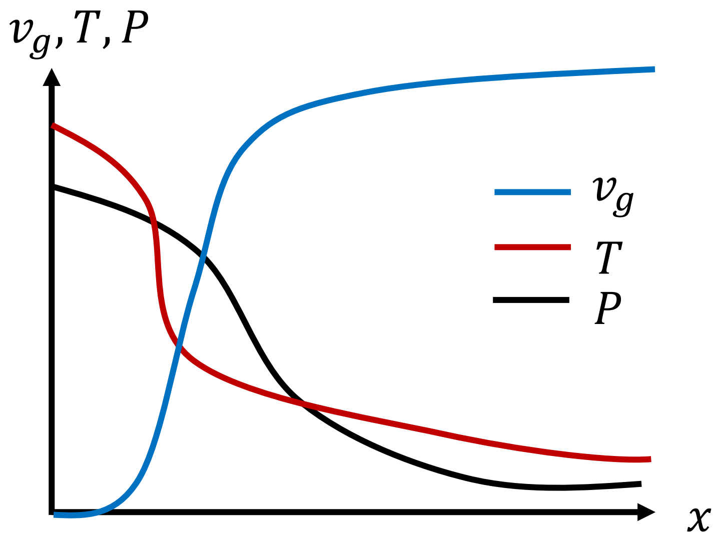
→ Optimal geometry

→ Exit particle velocity

[Alonso et al.] 2022, 2023

Evolution through the nozzle





- Applying the **Newton's second law** to one particle:

$$F_D = m_p a_p$$

F_D: Drag force

m_p: Particle mass

a_p: Particle acceleration

- The **drag force** is a function of the gas and particle velocities:

$$F_D = \frac{C_D \rho A_p}{2} \left(v_g - v_p\right)^2$$

C_D: Drag coefficient

ρ : Gas density

A_p: Cross section area

- The **gas velocity** is a function of the **Mach number, *M*** :

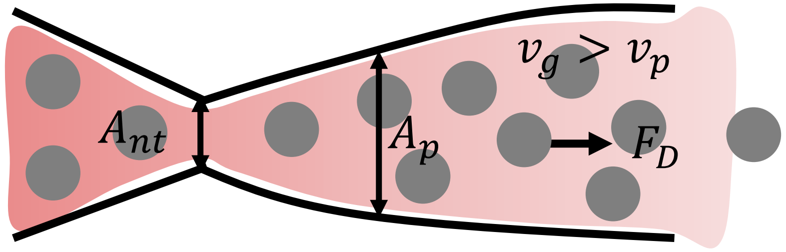
$$v_g = M\sqrt{\gamma R T}$$

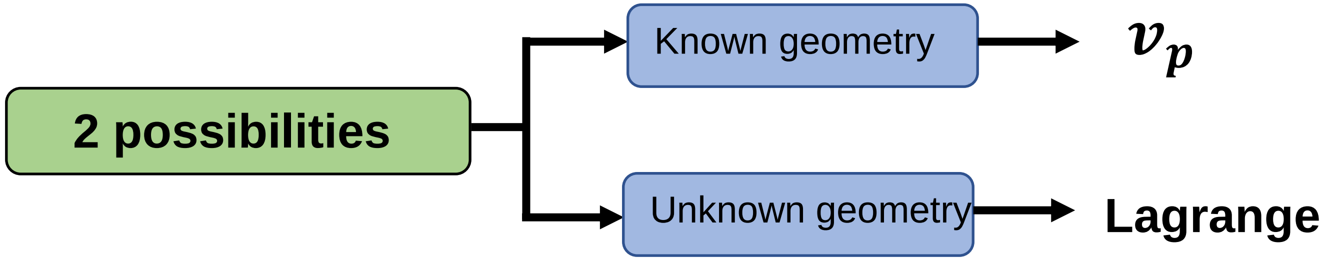
γ: Relationship between heat capacities

R: Gas constant

T: Temperature

Governing equations of the problem





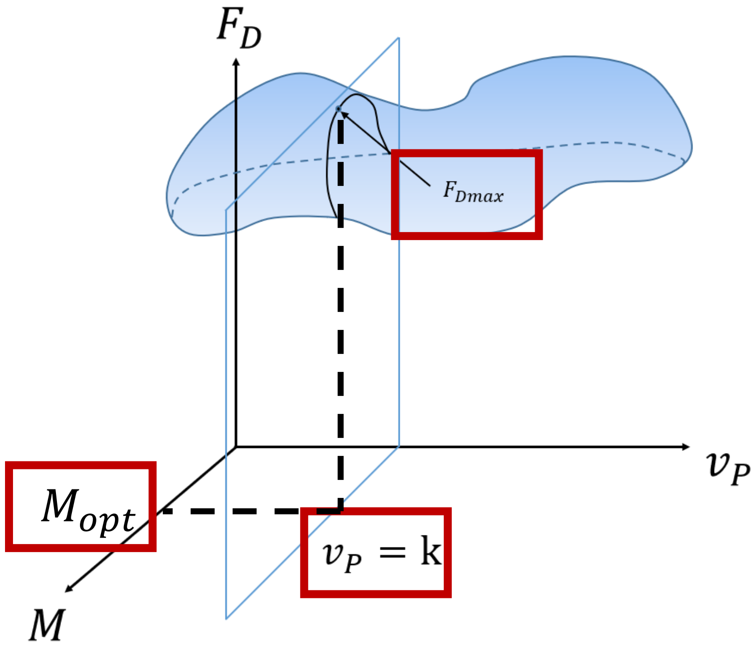
$$\nabla F_D = \lambda \nabla g \qquad g = v_p - k$$

- The **Mach number** can be related to the **cross section area**, A_p:

$$\frac{A_p}{A_{nt}} = \frac{1}{M}\left[\left(\frac{1}{\gamma+1}\right)\left(1 + \frac{\gamma - 1}{2}M^2\right)\right]^{\frac{\gamma+1}{2(\gamma-1)}}$$

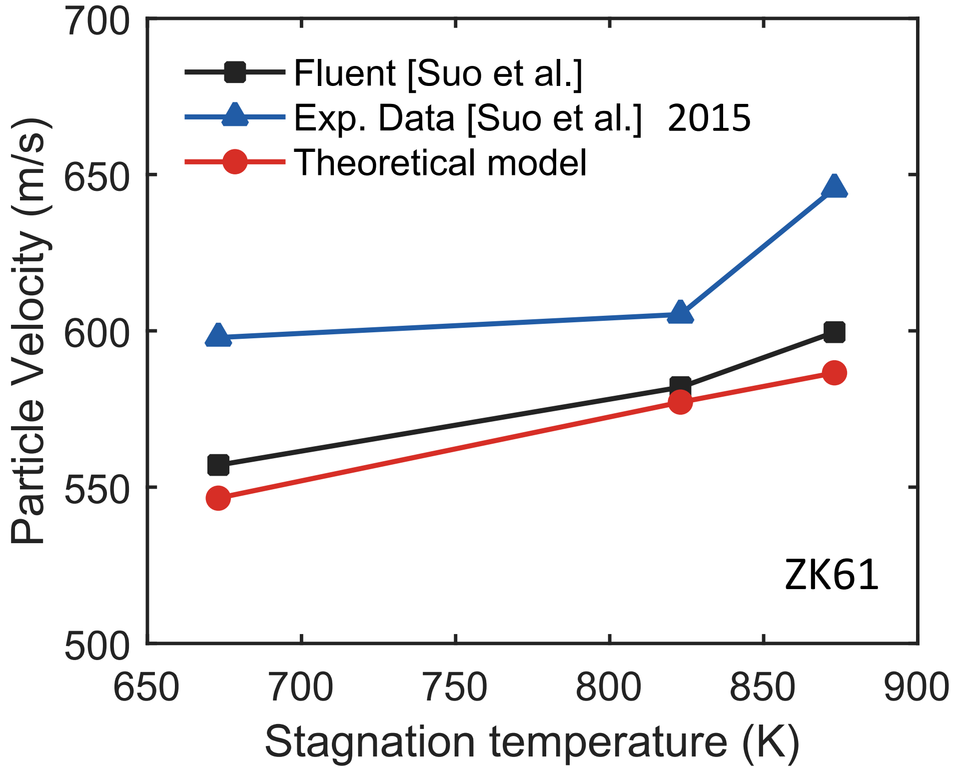
- The **governing equation** of the problem is:

$$\frac{dv_p}{dx} = \frac{C_D \rho A_p}{2 m_p v_p}\left(M\sqrt{\gamma R T} - v_p\right)^2$$
$$v_p(0) = v_0$$



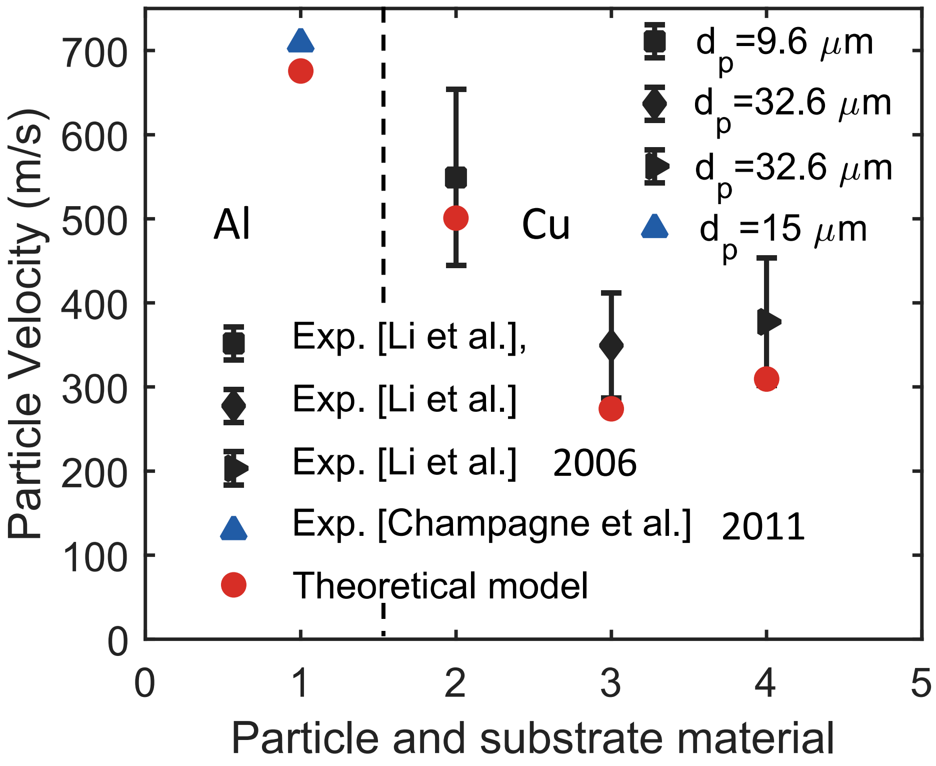
Validation of the model with experimental data

Does the **model predict** the particle velocity for **real geometries**?



$P_0 = 28\ bar$

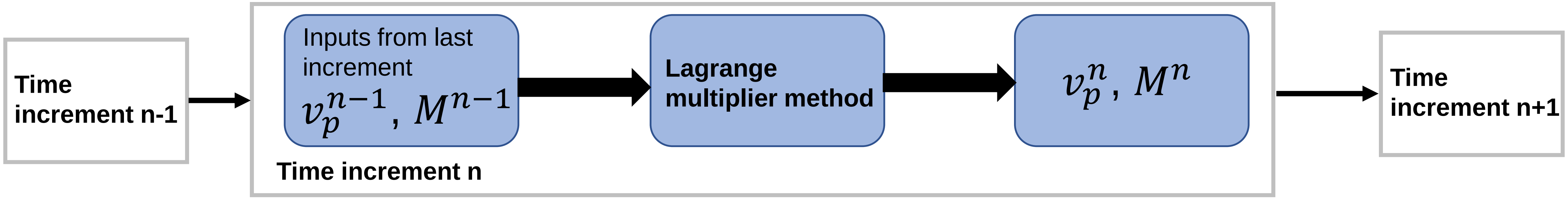
$d_p = 58\ \mu m$

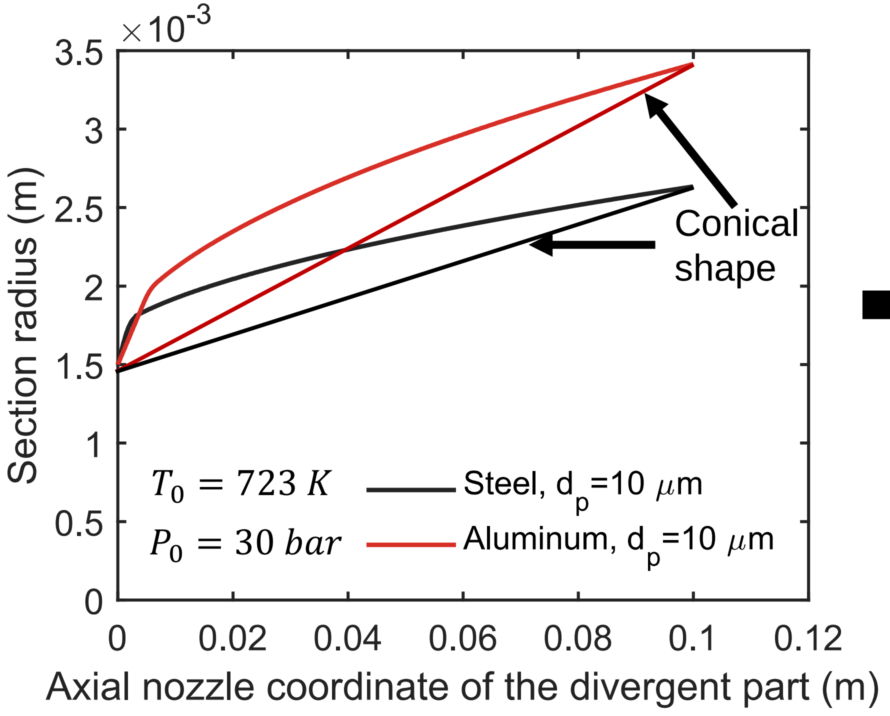


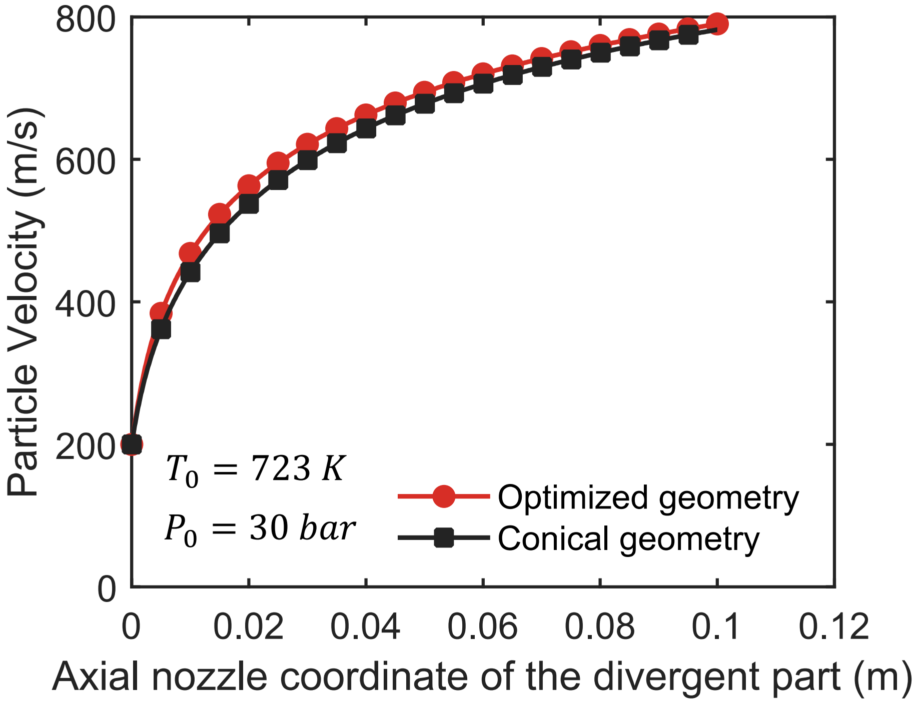
Al	Cu	
$P_0 = 32\ bar$	$P_0 = 20\ bar$	◆ $T_0 = 283\ K$
$T_0 = 588\ K$	■ $T_0 = 503\ K$	► $T_0 = 538\ K$

Optimal design

Governing differential equation:





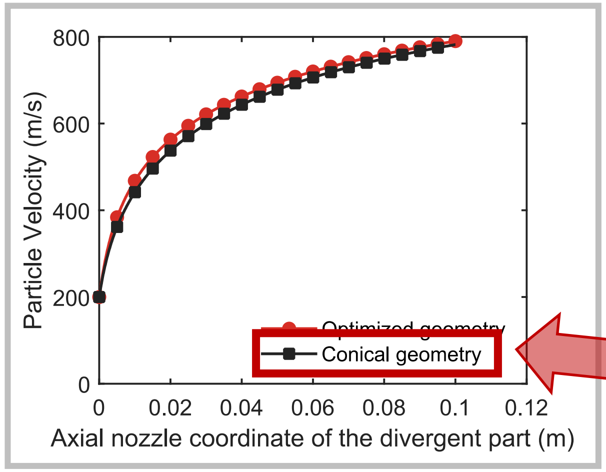


Quasi-optimal real design

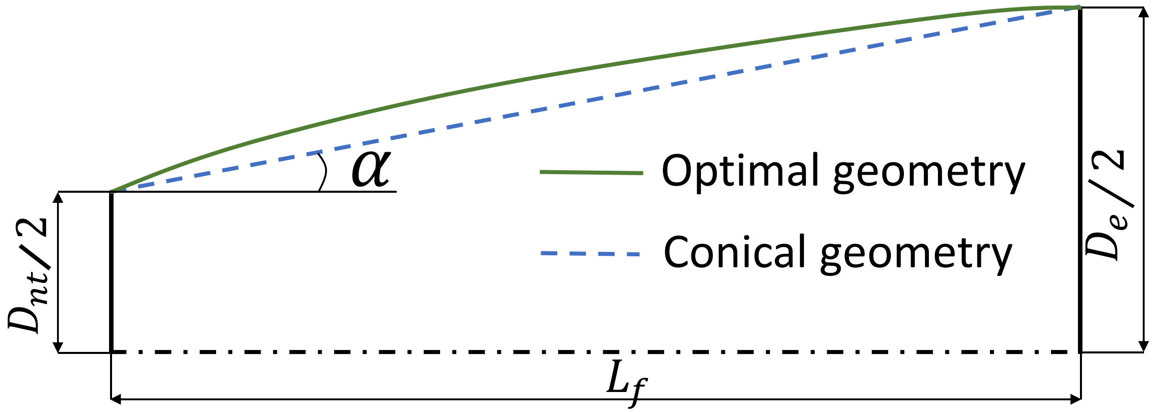
Optimal geometry

Conical geometry

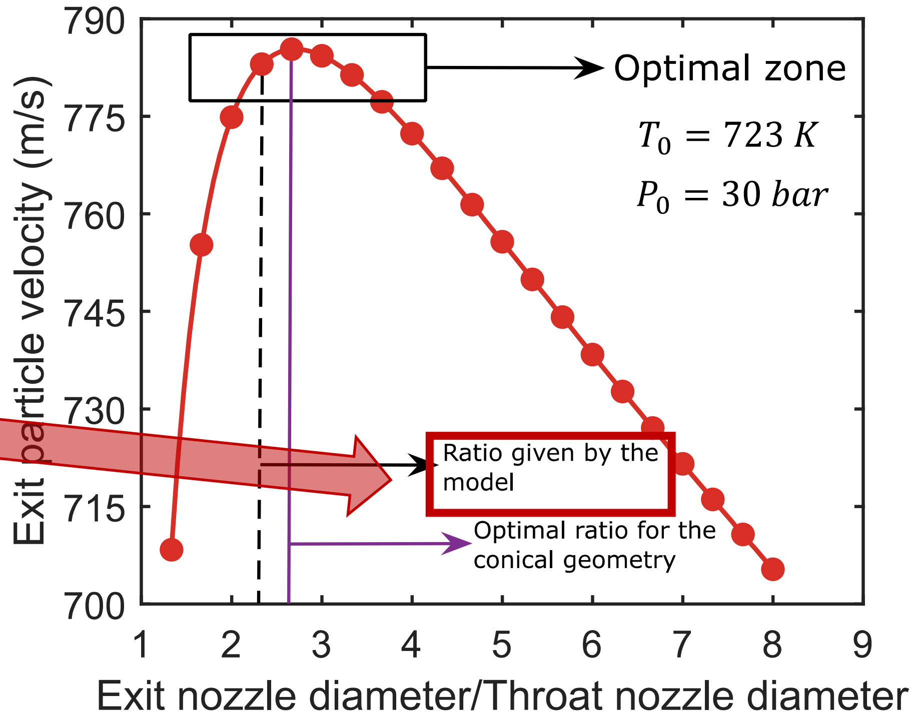
Small difference in the particle velocity



The conical geometry is easier to manufacture



Does the model provide the best conical shape for a nozzle?

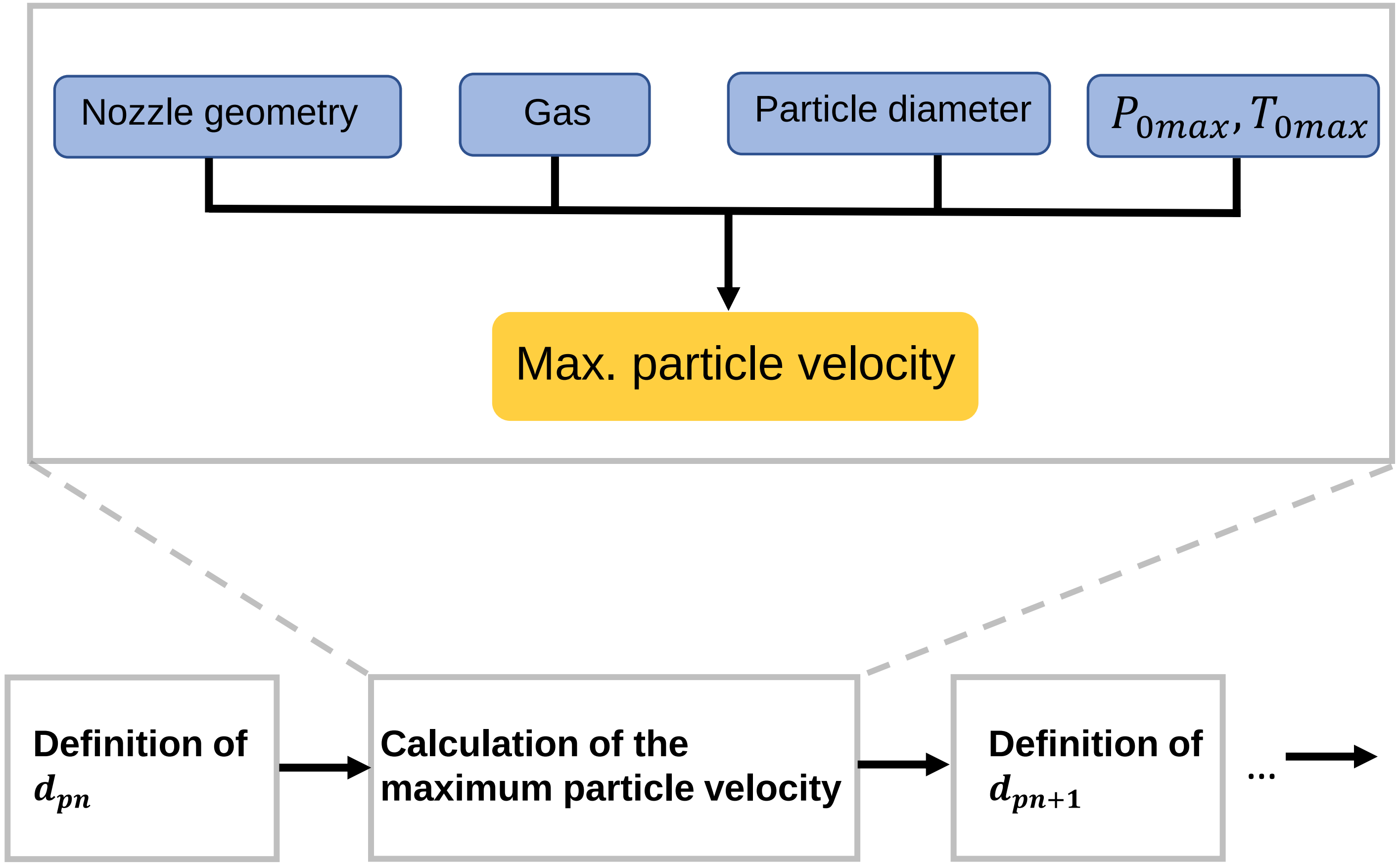


D_e/D_{nt}

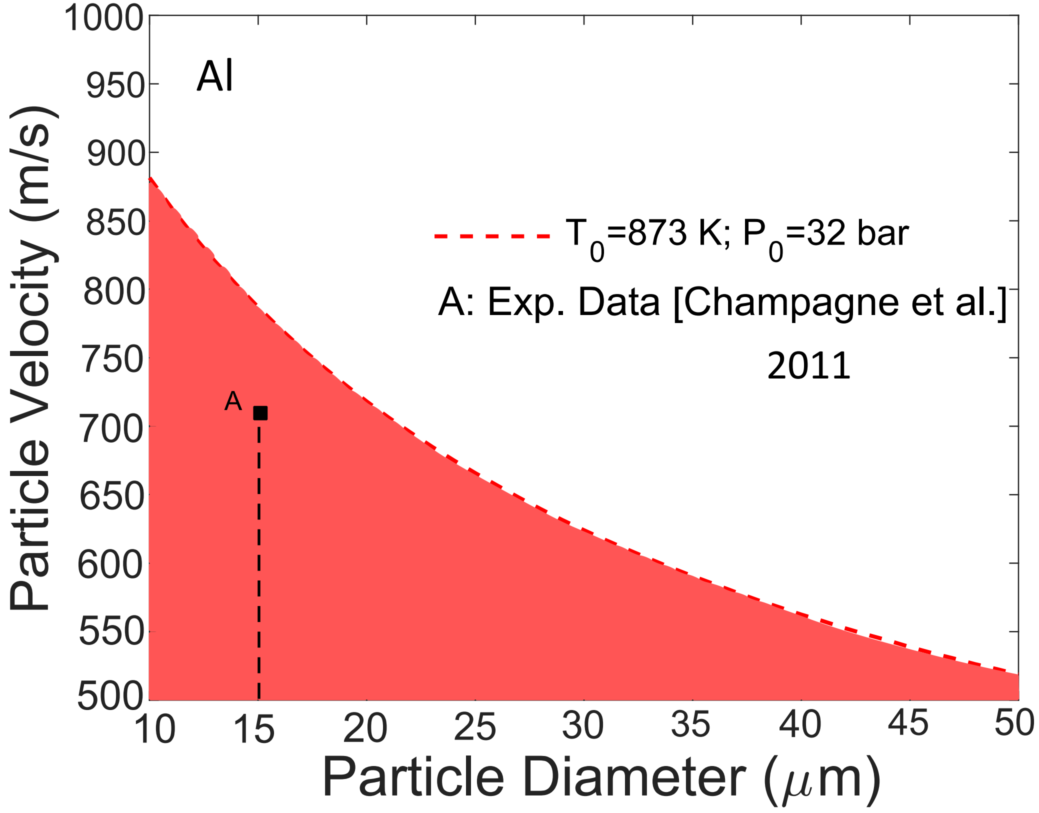
A conical geometry with the diameters given by the model is a reasonable design

Reachable particle velocities by an equipment

If the maximum operation conditions are known, the maximum particle velocity is obtained

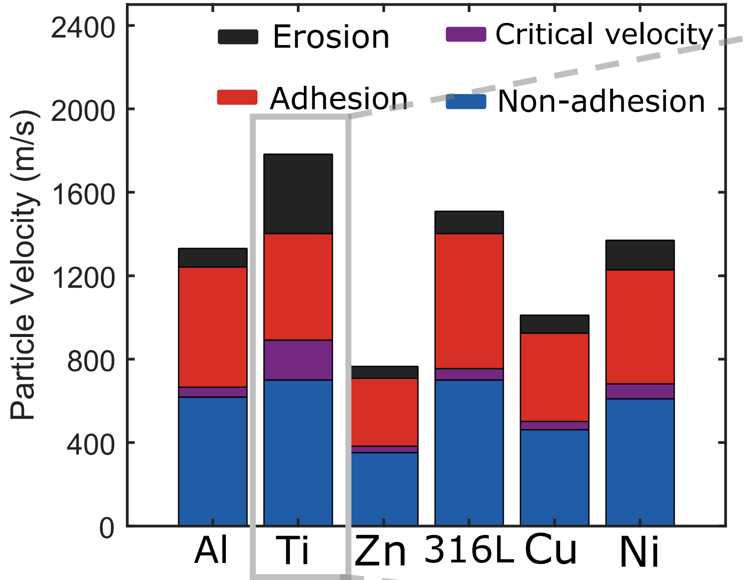


An area of the reachable particle velocities is obtained for a certain equipment

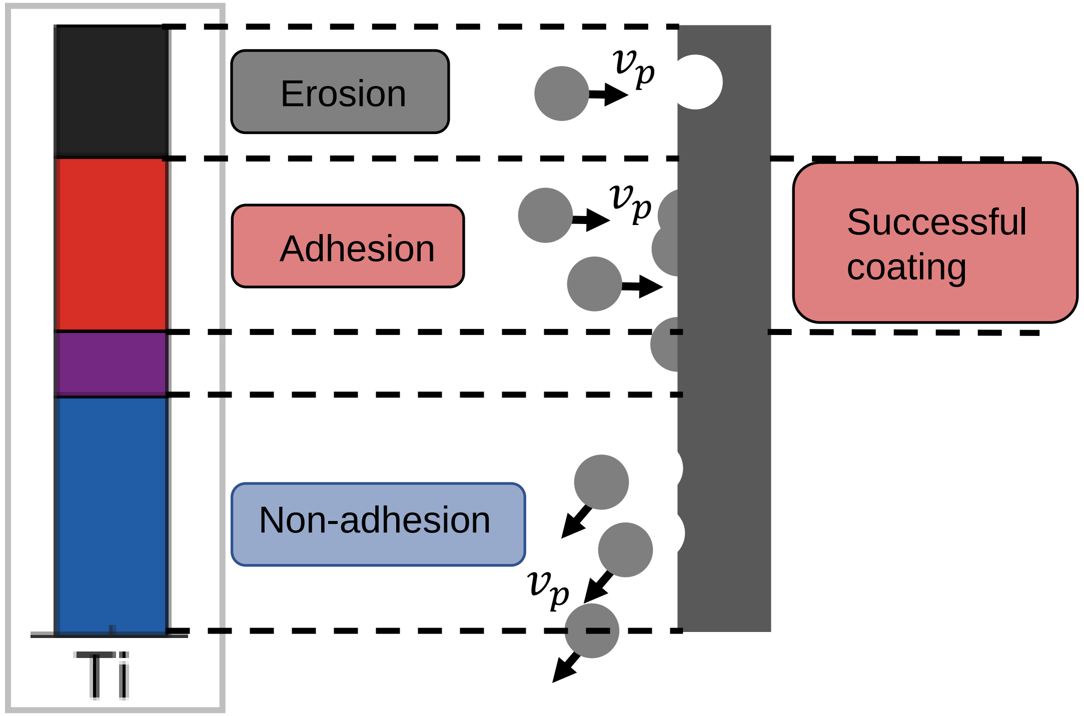


Adhesion and erosion limits

The particle velocity must be within a certain range to achieve adhesion



[Schmidt et al.] 2006



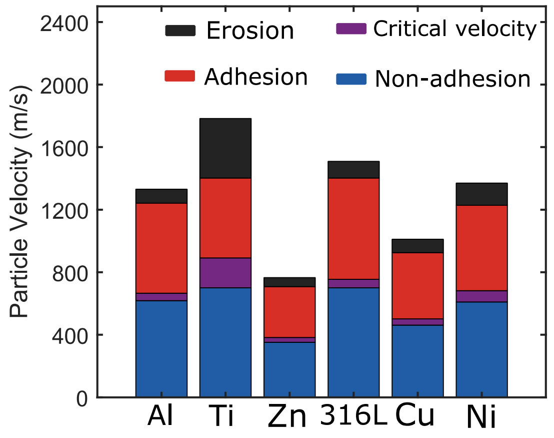
If $v_p < v_{cr}$ → Non-adhesion

If $v_{cr} < v_p < v_{er}$ → Adhesion

If $v_p > v_{er}$ → Erosion

Can an **equipment** propel the particles to velocities **within the adhesion window**?

Reachable adhesion window by an equipment



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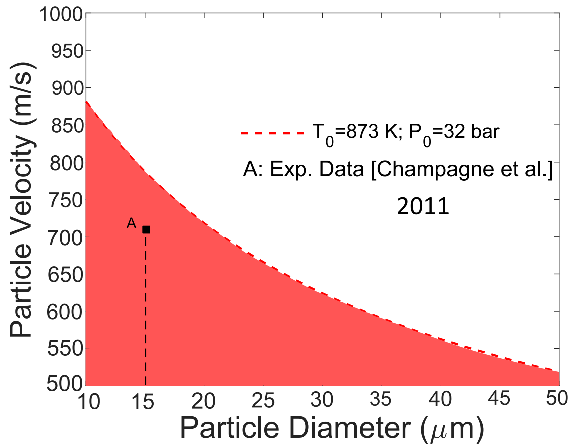
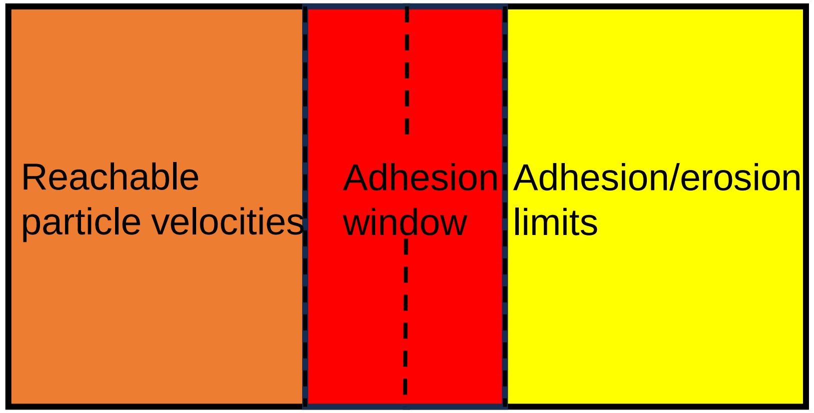
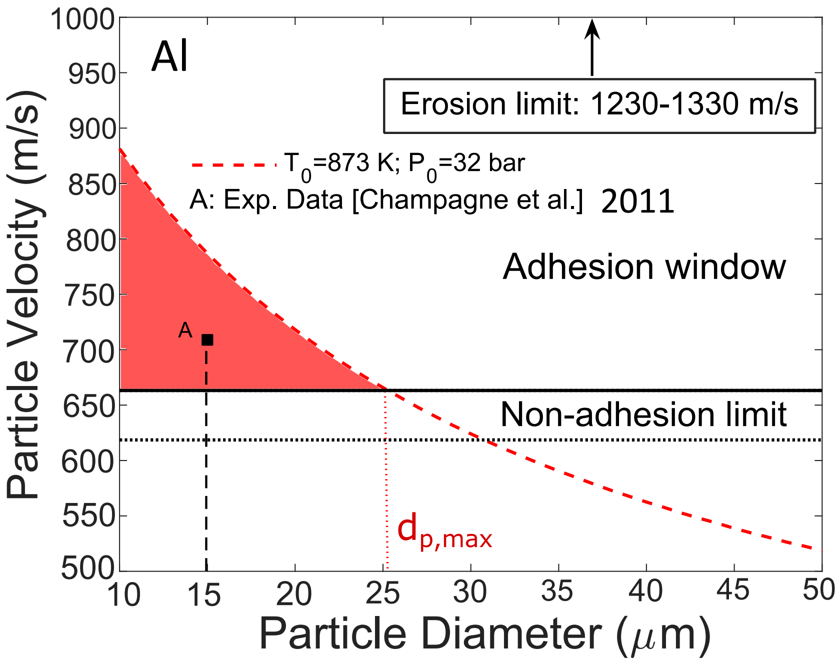


Adhesion window for an equipment/powder pair





It is proven that the experimental data A is on the predicted adhesion window

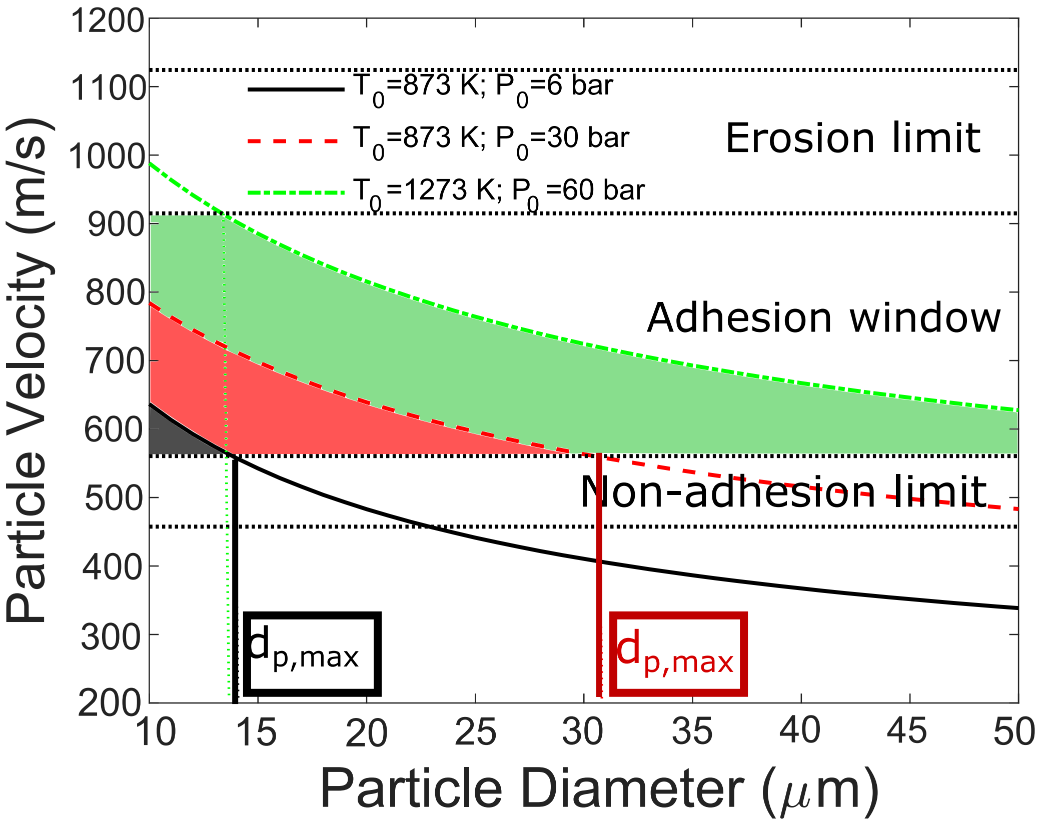
Adhesion windows for different equipment/powder

Cu particles

Adhesion window for a high pressure equipment

Adhesion window for a medium pressure equipment

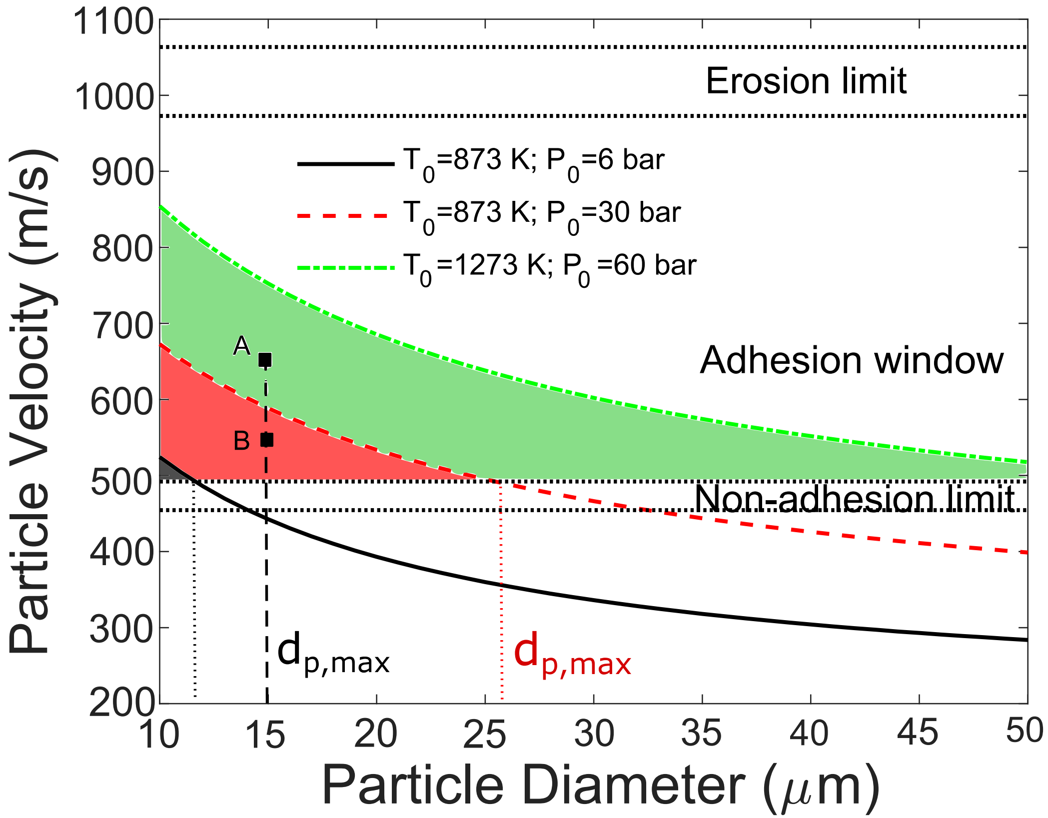
Adhesion window for a low pressure equipment



Ti particles

$d_p = 15\ \mu m$, B: Medium/ high pressure equipment

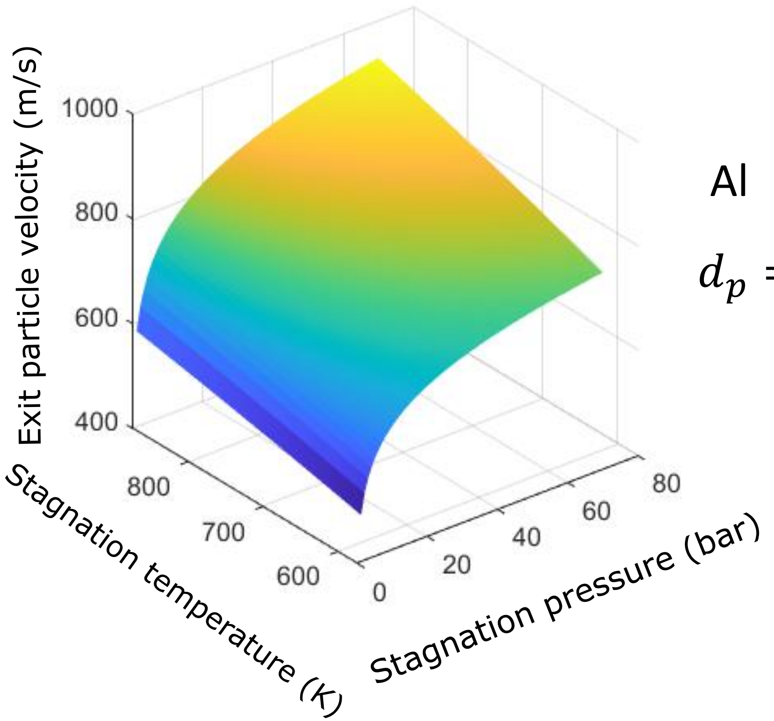
$d_p = 15\ \mu m$, A: High pressure equipment



Relating particle velocity to stagnation conditions

We can obtain maps relating the stagnation conditions with the particle velocity

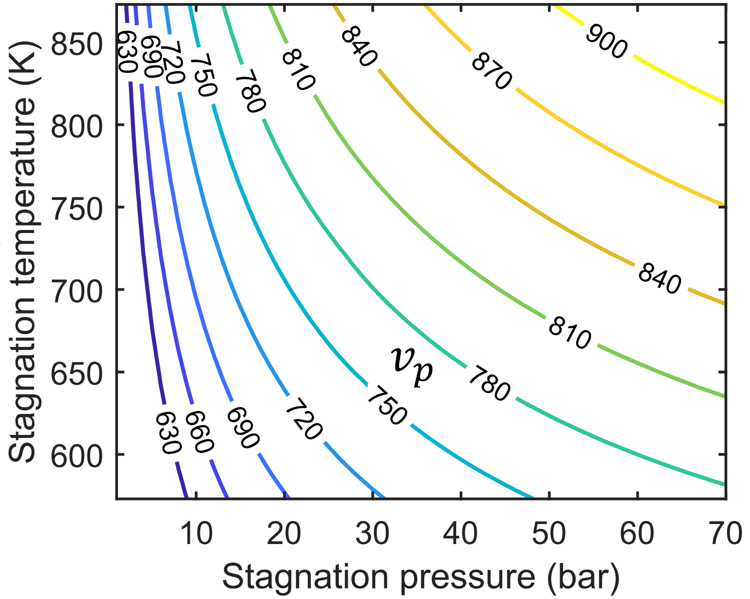
Nozzle geometry (optimized) | Gas | Particle characteristics



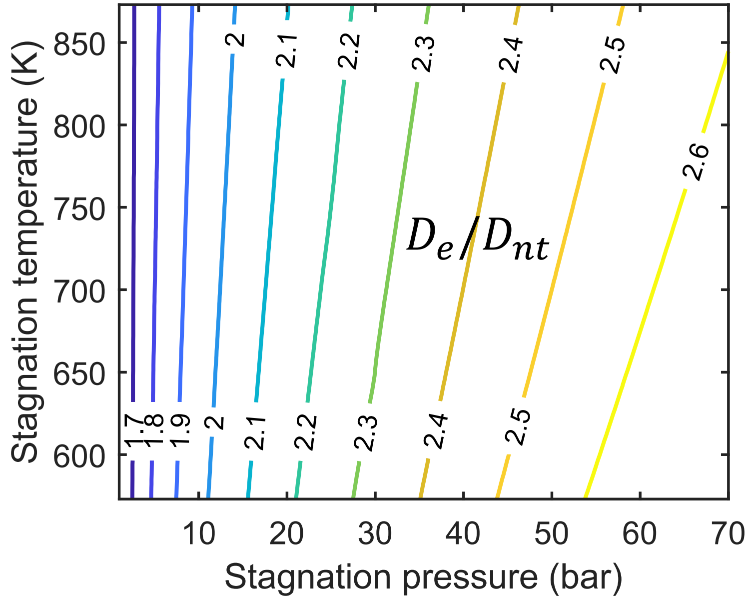
Al

$d_p = 10\ \mu m$

Contour plots of the particle velocity



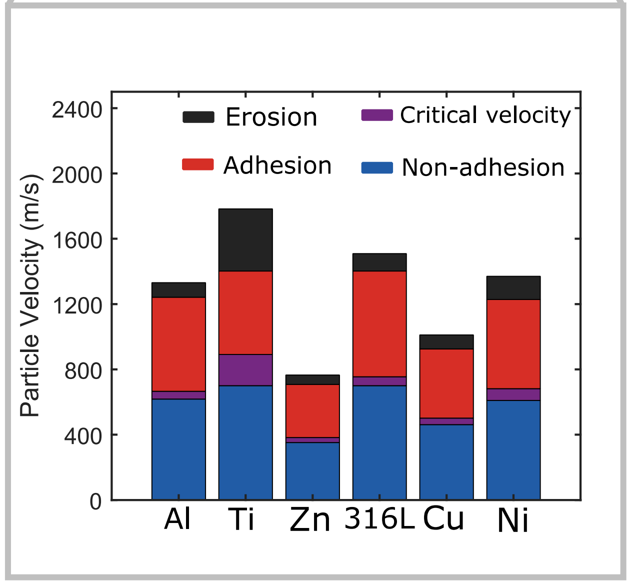
Contour plots of the diameter ratio

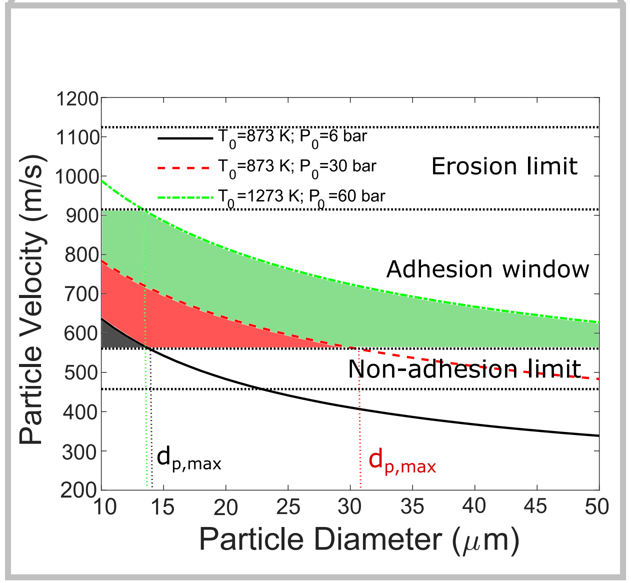


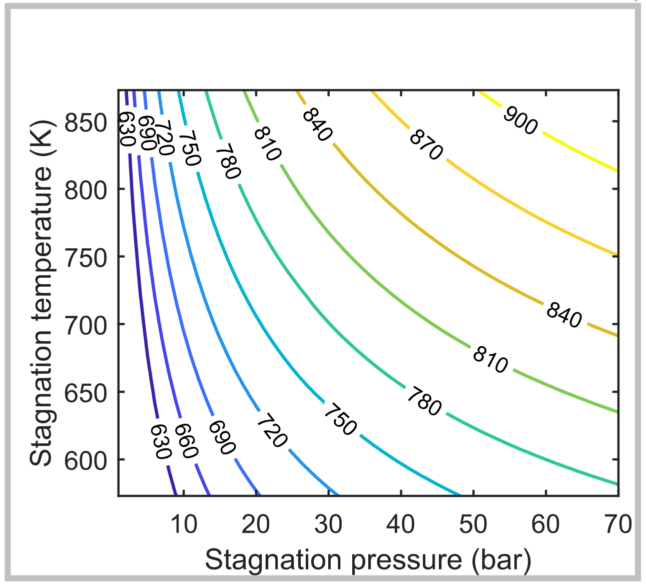
Blueprint for users

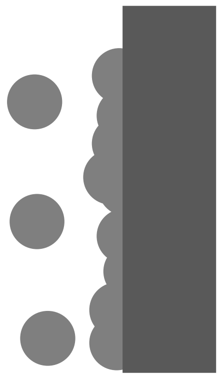
Inputs → **v_p needed for adhesion** → **Equipment to obtain v_p** → **Conditions that lead to v_p** → **Successful deposition!**

- Nozzle geometry
- Gas
- Particle characteristics









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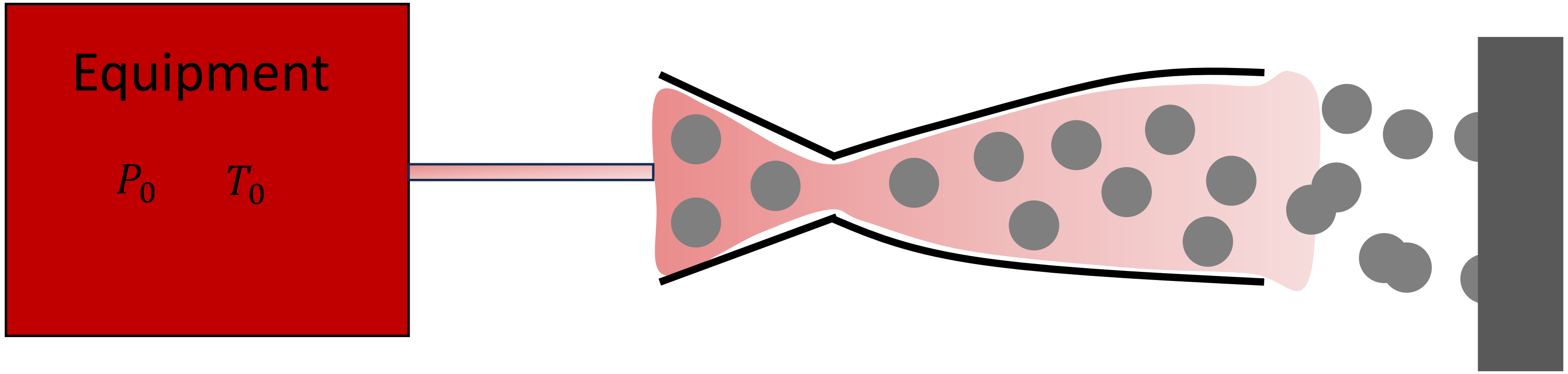

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