Tufts UNIVERSITY

The Negative Effect of Turbulences in Supersonic Gas Flow During Cold Spray

ME152 - High Reynolds Number Flow

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Summary - What did they do?

Article: Turbulences of the supersonic gas flow during cold spraying and their negative effects.

Authors: R.N. Raoelison, L.L. Koithara, S. Costil, C. Langlade

Focus:

- Study the negative impacts of turbulences in cold spray nozzles

Methodology

- Employ a 2D DNS study to get quantifiable velocity, pressure, vorticity and shear metrics
- Validate results with a physical shadowgraphy set up

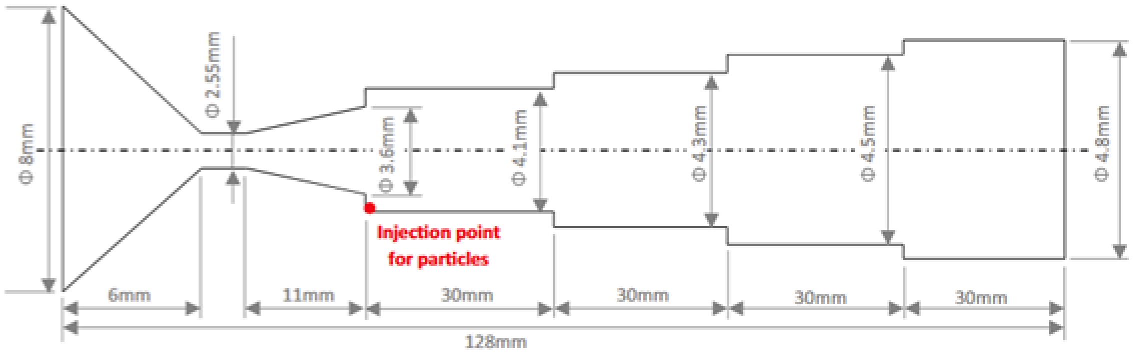

Figure 1: Nozzle Geometry used in DNS Study [1]

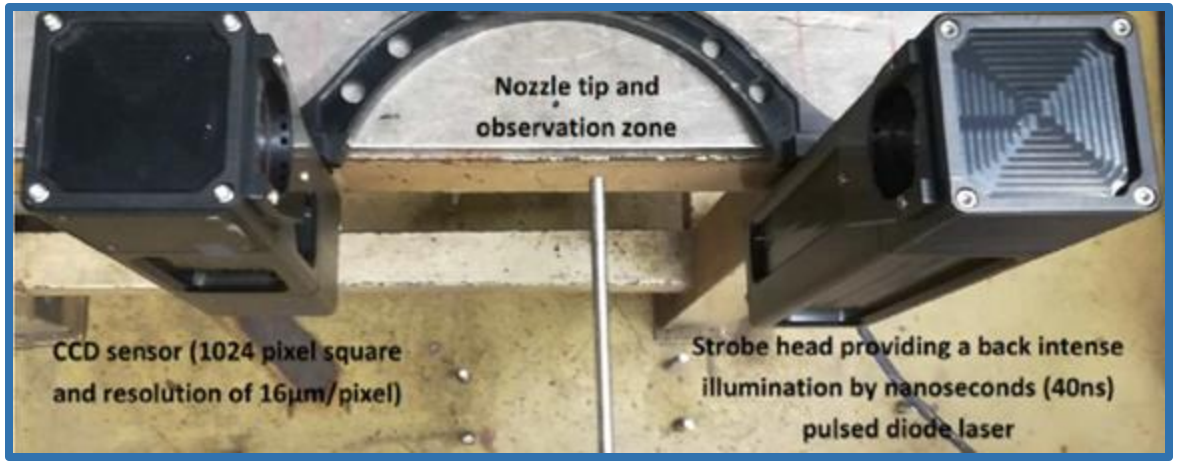

Figure 2: Shadowgraphy Testing setup including sensor and nozzle [1]

Summary - Results

Vorticity Generation

- Strong vorticity produced at particle injection port
- Interaction between expanding supersonic core and entrained cooler air amplified shear

Top-Wall Heating

- Turbulence-driven recirculation increased local heat flux on upper nozzle wall

Implications for Cold Spray

- Turbulence reduces particle heating → lower adhesion probability

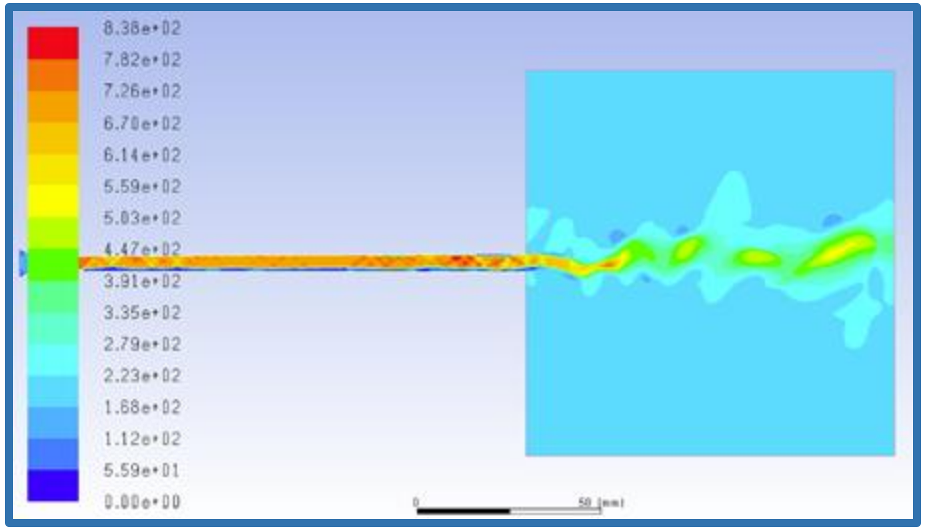

Figure 3: Expanded view of Gas Velocity in Nozzle and Free Stream [1]

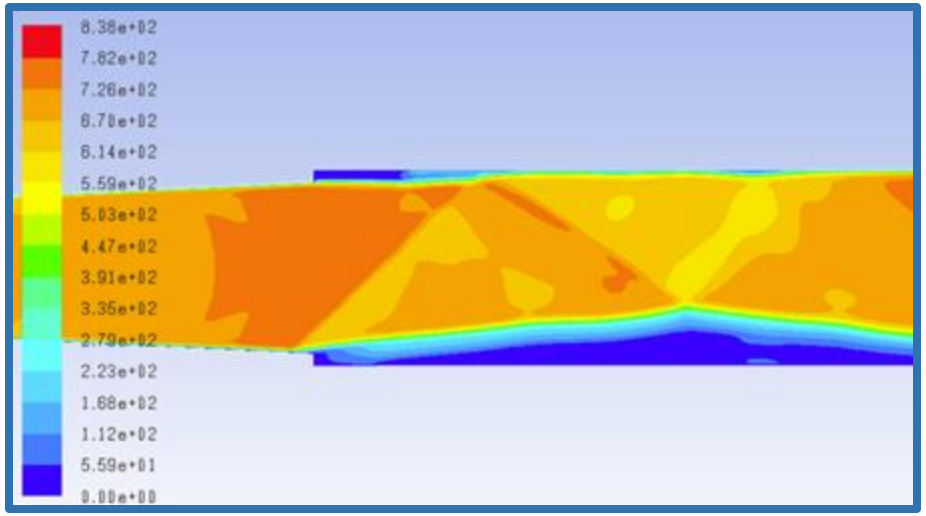

Figure 4: Concentrated view of Gas Velocity at Particle Feeding [1]

Technique - Direct Numerical Simulation

Geometry Considerations

- 2D nozzle geometry with a particle entry point upstream of nozzle exit
- Complexity of 2D DNS scales by **Re**$^{4/3}$ opposed to **Re**$^{9/4}$ for 3D geometries
- Solves for 2D compressible conservation of mass, momentum and energy

Boundary Conditions

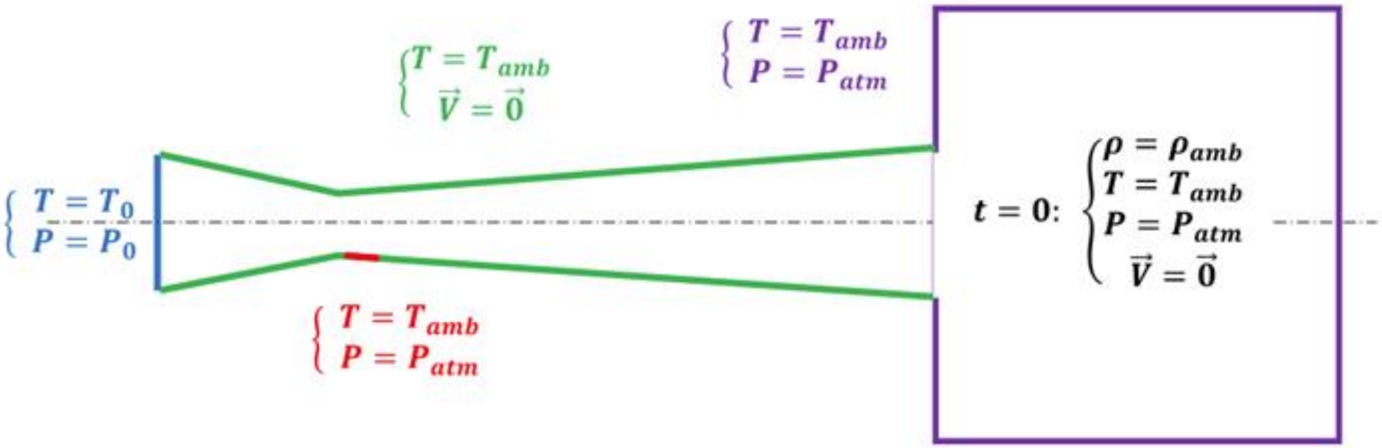

Figure 5: Boundary Conditions of Nozzle [1]

Table 1: Direct Numerical Simulation Characteristics [1]

Simulation Discretization			Computation Performance			Simulation Characteristics		
Nodes	Δt	Total Time	RAM	Core	Speed	CPU Time	Backup time	Storage
823,001	1 µs	0.05 s	144 GB	96	66.33 Tflops	36 h 14 m	1 ms	24.8 GB

Technique - Shadowgraphy

What is Shadowgraphy?

- Technique used to view flow fields based on refractive changes due to density differences
- Measured Intensity (I) is proportional to how fast the refractive index (n) is changing through space
  - Refractive Index is related to density change through Gladstone-Dale relationship

$$\frac{I(x,y) - I_0}{I_0} \propto -L\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)\int_0^{\Delta z} n(x,y,z)\, dz$$

Equation 1: Intensity relation for shadowgraphy applications [2]

Equipment - How is this Implemented?

- Pulsed Laser - Used to increase image clarity with 40 ns pulse length
- Charged Coupling Device (CCD) - 1024 pixels and a spatial resolution of 16 μm/pixel

Suitability of Study

Strengths

- DNS appropriate for capturing small-scale, unsteady turbulence critical in cold spray
- Accurate phenomenological description of shocks, vorticity, and jet oscillations

Limitations

- 2D simplification limits realism — turbulence is inherently 3D
- No mesh-convergence study; potential under-resolution of near-wall features

Consensus

- Despite limitations, method effectively demonstrated turbulence-driven nozzle wear

Table 2: Comparison of DNS Studies [1, 3]

Parameter	Cold Spray DNS [1]	Hypersonic STBLI DNS [3]
Geometry	2D CD Nozzle Cross Section	3D Compression Ramp
Flow Regime	V = 700 m/s (Supersonic)	$M_\infty = 6$
Mesh Size	70 µm	8 µm
Mesh Count	823,901	5.51×10^9
Computation System	CPU Cluster (96 Cores)	GPU Solver (OpenCFD-SCU)

Impact - Substrate Adhesion

Thermal History [4]

- DNS provides an understanding of how oblique shocks and mach disks form
- A better process of identifying particle thermal history can be identified

Particle Size and Material [5, 6]

- Qualitative dispersion characteristics notes in DNS study
- Particles smaller than 25 μm follow flow better due to low stokes number
- Particle weight ($\rho \times D$) is inversely and nonlinearly related to dispersion

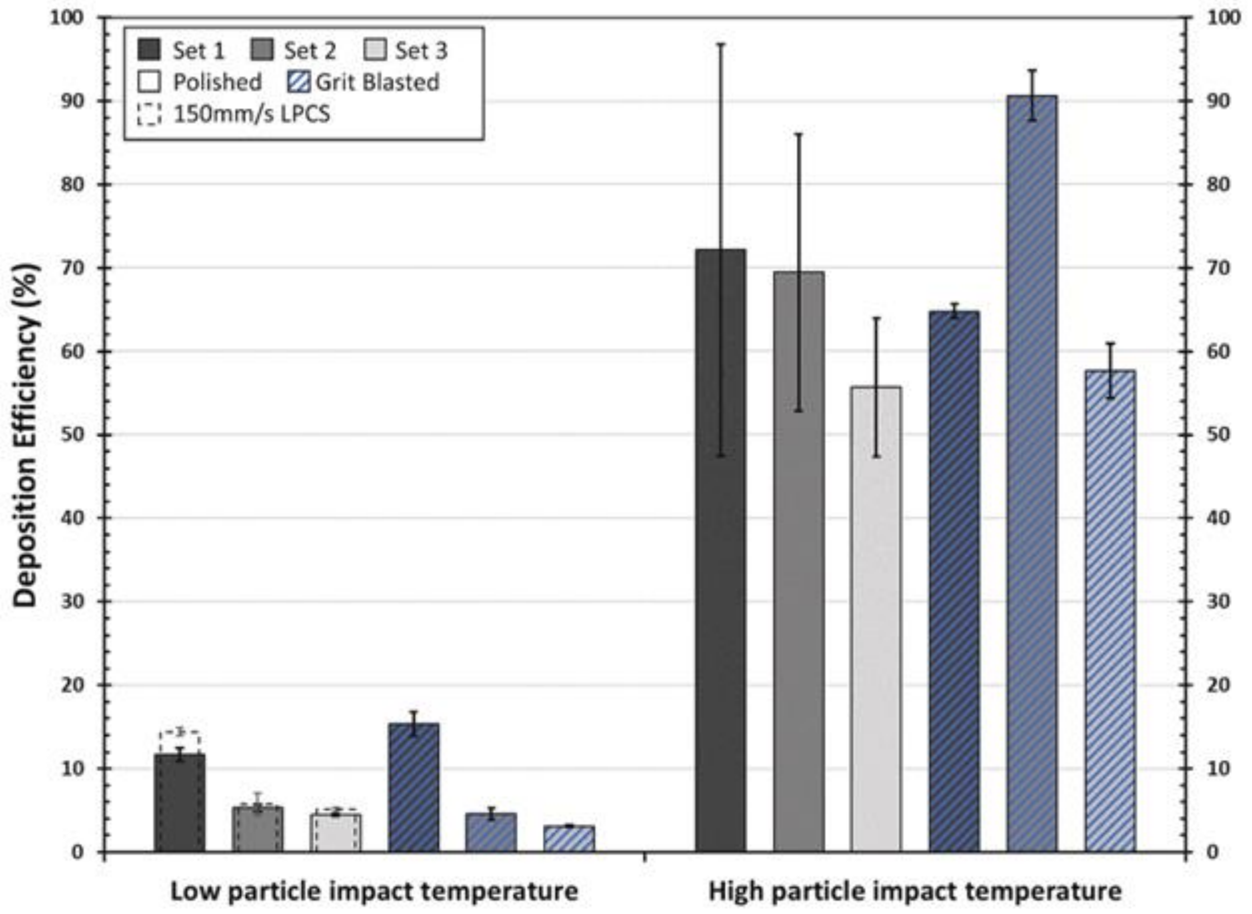

Figure 6: Impact of Particle Temperature on Deposition Efficiency [4]

Future Work - Flow Stabilization

Goal

- Reduce top-wall heating and asymmetry
- Improve nozzle lifespan

Approach

- Change original 2D DNS geometry to a full 3D Nozzle
- Introduce controlled secondary injections downstream of the powder port

Simulation Plan

- LES → Shown to work well with De Laval Nozzles [5]
- Mesh and Grid → Same as Parent article

Table 3: Flow Stabilization Simulation Plan [1]

Study Type	Fixed Parameter	Varied Parameter	Step Size
Pressure Study	Secondary Inlet Velocity 700 m/s	Pressure (0.40 MPa → 0.60 MPa)	0.02 MPa
Velocity Study	Secondary Inlet Pressure 0.50 MPa	Velocity (650 m/s → 750 m/s)	10 m/s

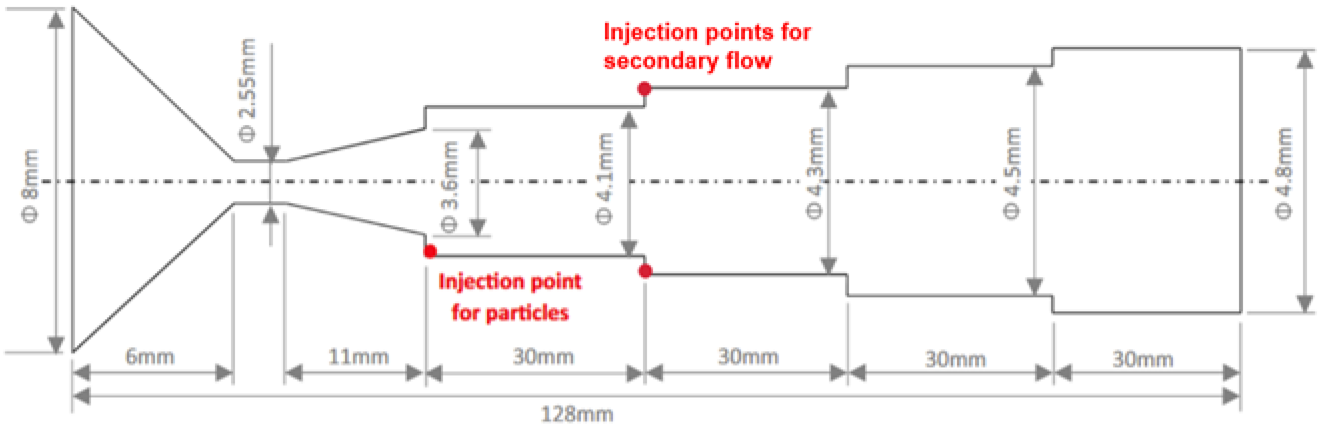

Figure 7: Nozzle Geometry with Indicated Flow Entry Points [1]

References

[1] Raoelison, R.N., Koithara, L.L, Costil, S. and Langlade, C. "Turbulences of the supersonic gas flow during cold spraying and their negative effects: A DNS CFD analysis coupled with experimental observation and laser impulse high-speed shadowgraphs of the particles in-flight flow." International Journal of Heat and Mass Transfer Vol. 147 (2020). DOI 10.1016/j.ijheatmasstransfer.2019.118894

[2] Gopal, Amrutha, Minardi, Stefano and Tatarakis, Michael. "Quantitative two-dimensional shadowgraphic method for high-sensitivity density measurement of under-critical laser plasmas." Optics Letters Vol. 32 (2007). DOI 10.1364/OL.32.001238

[3] Zhang, Ji, Guo, Tongbiao, Dang, Guanlin and Xin-Liang, Li. "Direct numerical simulation of shock wave/turbulent boundary layer interaction in a swept compression ramp at Mach 6." Physics of Fluids Vol. 34 (2016). DOI 10.1063/5.0118578.

[4] Nastic, A., Jodoin, B., Poirier, D. and Legoux, J.-G. "Particle temperature effect in cold spray: A study of soft particle deposition on hard substrate." Surface Coatings and Technology Vol. 406 (2021). DOI 10.1016/j.surfcoat.2020.126735.

[5] Mahato, Bikash, Yoder, Jay, Simmons, Gloyd, Huft, Nathan, Nault, Isaac and Lucon, Peter. "Particle dynamics in low-pressure cold spray additive manufacturing — A numerical and experimental study." Additive Manufacturing Vol. 10 (2025). DOI 10.1016/j.addma.2025.104937.

[6] Koithara, Libin Lalu, Raoelison, Rija Nirina and Costil, Sophie. "Flow phenomenon of micron-sized particles during cold spray additive manufacturing: High-speed optic observation and characterization." Advanced Powder Technology Vol. 31 (2020). DOI 10.1016/j.apt.2019.12.037

Thank You!

Questions?