Particle Acceleration Through Coaxial Co-Flow Nozzles for Cold Spray Applications

Amit Kumar Sharma[1,*], Ashish Vashishtha[1], Dean Callaghan[2], Cathal Nolan[1], Srinivasan Bakshi[3], M Kamaraj [3], Ramesh Raghavendra [4]

[1]Department of Aerospace, Mechanical and Electronic Engineering, Institute of Technology Carlow, Ireland

[2]The Center for Research and Enterprise in Engineering (engCORE), Institute of Technology Carlow, Ireland

[3]Department of Metallurgical and Material Engineering, Indian Institute of Technology Madras, India

[4]SEAM Research Centre, School of Engineering, Waterford Institute of Technology, Waterford, Ireland

Abstract The present study numerically investigates the effectiveness of co-flowing nozzle for cold spray application. A convergent - divergent axi-symmetric nozzles have been simulated with high-pressure nitrogen flow. The particle acceleration is modelled by 2-way Lagrangian approach and validated with literature. An annular co-flowing nozzle with circular central nozzle has been simulated for nitrogen gas flow. The momentum preservation for central nozzle flow has been observed, which results in higher particle speed for longer axial distance after nozzle exit. It is envisioned from the outcome that utilization of co-flow can lead to reduction in the divergent section length of cold spray central nozzle, which may ultimately help to address clogging issues for continuous operation. Co-flow operating at 3 MPa, same as central nozzle can increase supersonic core up to 23.8 %.

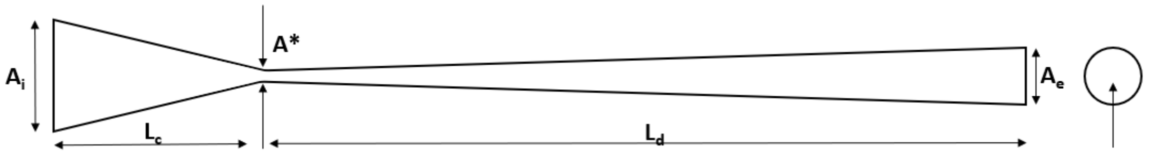
Keywords: Cold spray, Co-flow, Nozzle Design, CFD, Supersonic Jet

1 Introduction

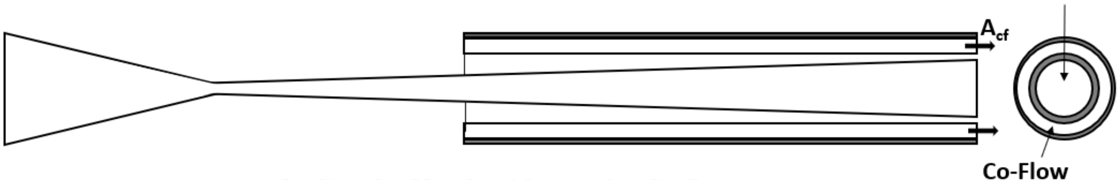
The cold gas dynamic spray (CGDS) process is an emerging non-thermal deposition method that has gained a lot of attention from scientists and the industrial community due to its vast potential for additive manufacturing applications [1]. In the cold spray process, bonding takes place when the velocity of the particles, which are accelerated by high pressure and pre-heated supersonic gas stream, exceed a critical velocity, but remain below the erosion velocity [2]. The performance of cold spray system from powder acceleration to deposition quality and efficiency are governed by power and substrate material along with particle acceleration with carrier gas by nozzle. The current cold spray system faces two main challenges in long continuous operations: 1) high consumption of carrier gas, 2) clogging of long divergent section of nozzle. Nitrogen and Helium are two mainly used carrier gases [3]. However, the supersonic nozzle is the heart of cold spray system, very few studies at present deal with nozzle designs to improve the efficiency and build quality of the deposition. In this study, a coaxial co-flow nozzle is introduced with motivation to provide an imaginary wall of high-speed fluid around primary carrier gas, which can lead to reduce the divergent section length. In future, the operation of coaxial system with different gases can reduce main carrier gas consumption too. The co-axial nozzles previously experimentally studied in open-jet facility as sonic co-flow with supersonic central jet [4, 5]. At all the operating conditions, it is found that sonic co-flow surrounding the supersonic jet not only increases the supersonic core length by increasing number of shock-cells, but also preserve momentum in decay zone of jet too. The increase in supersonic core length of gas flow, can increase the particle penetration length. The higher particle penetration length can enable to reduce the divergent section length, which can ultimately reduce the clogging and provide longer continuous operation of system. Recent computational fluid dynamics (CFD) [6, 7] studies of cold spray process enables to evaluate performance of such conceptual designs of nozzles before performing the experimental studies. A typical circular cross-section supersonic nozzle of cold spray system is shown in Fig. 1a, which is adopted from the work of Meyer et al. [6]. In this study, a co-flowing annular straight channel is attached to the divergent section, which allows the central jet to expand into the sonic annular flow as shown in Fig. 1b. The primary jet and co-flow jet are operated with same gas but different pressure, the powder fed into central nozzle. The particle acceleration in presence of co-flow is compared with different operating pressures with reduced nozzle length. The main objectives of the study can be highlighted as: 1) Understand the effectiveness of annular flow around cold spray nozzle for particle acceleration, 2) Enhance particle acceleration in reduced size nozzle with co-flow. In the next sections, adopted CFD simulations method and obtained results are discussed. It is expected that the secondary flow in co-flow nozzles [5] will reduce the growth rate of the primary shear layer and delay the mixing of the primary jet causing the primary supersonic core's elongation.

2 Numerical Methodology

All the numerical simulations are performed using ANSYS FLUENT 2021 R1 with gas and particle simulation using two-dimensional axi-symmetric computational domain.



(a) Circular Nozzle



(b) Circular Nozzle with Annular Co-flow

Figure 1. Design of Co-flowing nozzle

2.1 Geometry and Computational Domain

A schematic illustration of the cold spray nozzle and newly incorporated co-flow design employed in this numerical investigation is shown in Fig. 1. The selected converging-diverging nozzle have a circular cross-section. L_c and L_d are the length of converging and diverging sections of nozzle, respectively. A_i, A_e and A^* represents the inlet, exit and throat cross-sectional area of the nozzle with values as 314 mm^2, 28.3 mm^2 and 3.1 mm^2 respectively. A_{cf} quantifies the area of the co-flow section. The exit to throat area ratio and convergent section was kept same for all the nozzle design while varying the divergent length for the co-flow nozzle. Table 1 summarizes the corresponding values of all the four designs (N210, L210, L170 & L110). A straight chamber is attached in the beginning of the convergent section of the nozzle to stabilize the gas flow. The computational domain comprises of stagnation chamber, the nozzle along with co-flow region and an extended expansion region. A two-dimensional axi-symmetric model was utilized in the analysis with quadrilateral elements which allows a considerable reduction in computational time without compromising with the results. With around 121,000 elements for L210, the structured mesh was constructed to complement the respective flow phenomena and tested to provide a mesh-independent solution for the gas phase. It was fine-tuned in the near-wall region to capture the boundary layer flow properly. The throat and exit region of nozzle was resolved adequately to visualize flow gradient and capture the shock patterns. Special attention was paid at the exit refinement such that there is no change in solution of flow pattern.

Table 1: Geometric Details and Simulated Cases (NCF- Without Co-Flow, CF- With Co-Flow)

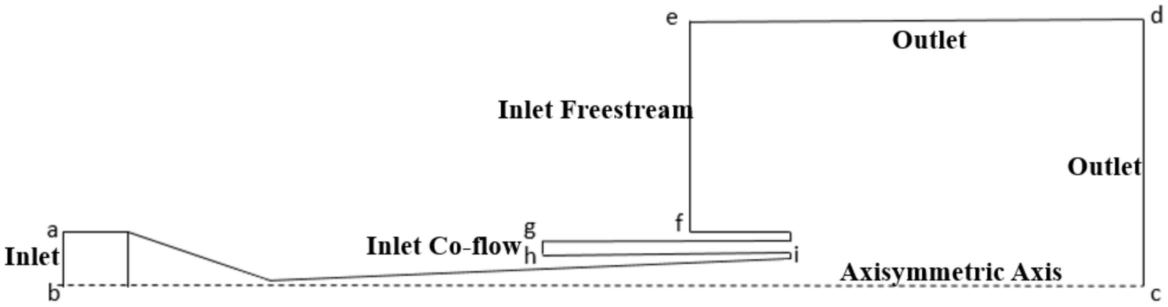
	Condition	Central Nozzle	Co-flow Nozzle	L_c, L_d (mm^2)	A_{cf} (mm^2)
N210	NCF	3 MPa, 623 K	-	30, 180	-
L210	CF	3 MPa, 623 K	0.5, 1, 3 MPa, 300 K	30, 180	40.05
L170	CF	3 MPa, 623 K	0.5, 1, 3 MPa, 300 K	30, 140	40.05
L110	CF	3 MPa, 623 K	0.5, 1, 3 MPa, 300 K	30, 80	40.05

2.2 Boundary Conditions

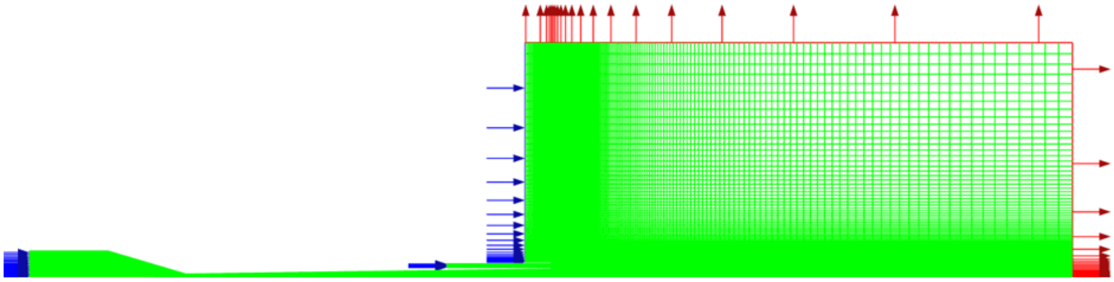
The boundary conditions at the nozzle inlet (pressure inlet) were set to 3 MPa and 623 K in all the simulated cases, while atmospheric static pressure was set at the model's outlet zone. At co-flow nozzle inlet the three different pressures were applied in order to understand the influence on particle acceleration and enhancement of primary flow core length. Stagnation chamber has negligible velocity thus total and static temperature and pressure are equal. For both primary inlet and co-flow, the turbulence intensity is 2% and length scale is set to 10% . An extended domain was created at the exit of nozzle with the goal of analyzing particle's velocity profile. For simulating the without co-flow case the co-flow inlet was kept as wall and rest everything was kept constant. Titanium powder particle of 45 μm was chosen for all particle injection analysis and were injected from nozzle inlet.

2.3 Simulation set-up

All the different nozzle configurations as mentioned in Table 1 were simulated with two-dimensional axi-symmetric solver. In order to account for the compressibility effect, ideal gas law is used for density calculation



(a) Computation Domain



(b) Computational Grid

Figure 2. (a) Schematic of Computational domain and (b) Medium Grid selected for simulation

Table 2: Boundary condition (BC)

	Name	Condition Type	p_0	$\vec{v}$	T_o	DPM
BC1	Inlet	Pressure Inlet	specified	$\frac{\partial \vec{v}}{\partial n} = 0$	specified	injection
BC2	Inlet co-flow	Pressure Inlet	specified	$\frac{\partial \vec{v}}{\partial n} = 0$	specified	escape
BC3	Far-field	Velocity Far-field	specified	$\frac{\partial \vec{v}}{\partial n} = 0$	$\frac{\partial T}{\partial n} = 0$	escape
BC4	Outlet	Pressure Outlet	specified	$\frac{\partial \vec{v}}{\partial n} = 0$	$\frac{\partial T}{\partial n} = 0$	escape
BC5	Wall	Adiabatic no-slip	$\frac{\partial p}{\partial n} = 0$	$\vec{v} = 0$	$\frac{\partial T}{\partial n} = 0$	reflect

and nitrogen as the process gas. Nitrogen displays less than 4 % variation from ideal gas value up to 10 MPa pressure and 900 K temperature, respectively supporting the choice of the ideal gas behaviour. In highly compressible flow, viscosity of the gas tends to change with temperature, thus 3-coefficient Sutherland law is utilized since its widely recommended for supersonic gas flows. A implicit density-based solver was used under steady state condition as it responds very well to compressible flows in the supersonic region. Advection Upstream Splitting Method (AUSM) scheme is employed as the flux type along with Green-Gauss node based gradient method for discretization. Simulation for flow field were solved with second-order accuracy till necessary number of iterations to reach admissible level of convergence. As the flow field lacks regions of flow separation or re-circulation, the 2 equation standard k-ε model of turbulence was found adequate for the present study. High order term relaxation (HOTR) and Convergence acceleration for stretched meshes (CASM) were switched on to accelerate convergence in Density based solver (DBS-implicit) along with solution steering. FMG initialization method was opted to get good initial solution for solver to start calculation and thereby reducing the computational time. Particle injection into the nozzle inlet were carried out using discrete phase modelling algorithm. A two-way Lagrangian approach was utilized to simulate particle acceleration, its trajectories and effect of the particle phase on the gas phase. The two-way coupling method are more effective in giving realistic results close to experimental values. Furthermore, high-Mach number drag law was opted to include the effect of compressibility. The stochastic - tracking type model discrete random walk (DRW) was opted to account for particle dispersion due to turbulence effects. By using this, generation of a fluctuating velocity part is realized by Gaussian distribution function.

2.4 Grid Independence

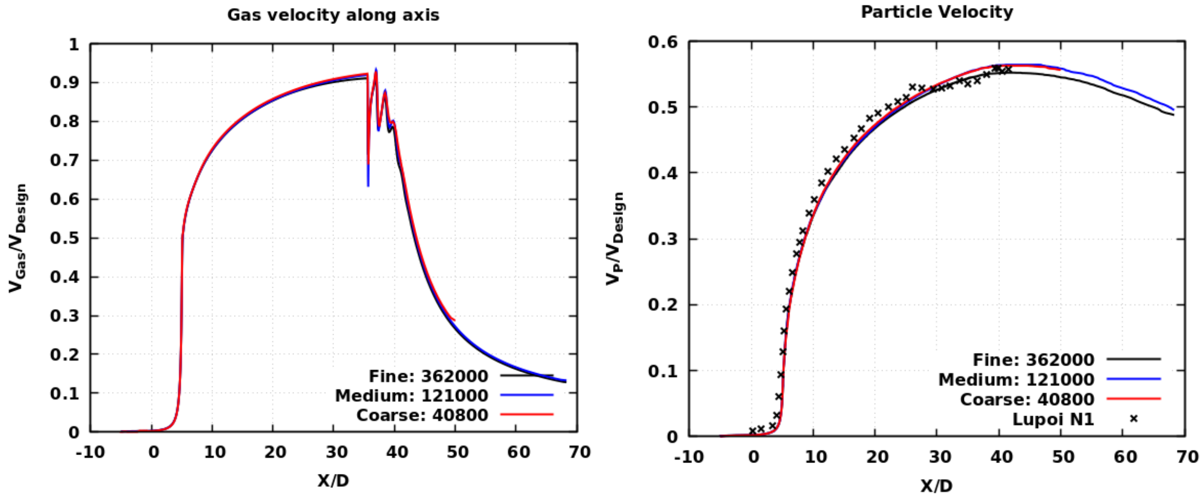
Three different sizes of grids Coarse (40800 elements), Medium (12100 elements) and Fine (362000 elements) were used to simulate the central nozzle without co-flow. Particles were injected at the nozzle inlet and particle velocity has been plotted along the axial location. Figure 3 shows the simulated gas and particle speed, which is non-dimensionalized by design gas speed delivered by nozzle operating with nitrogen at 623K, as explained in Eq. 1, 2, 3 where, R_U is universal gas constant, γ is specific heat ratio, MW_{gas} is molecular weight of carrier gas. All three grid resolutions, the gas phase speed remains almost similar in nozzle exit speed as well as fluctuations after the nozzle exit, representing shock-cells in the flow field. The particle acceleration obtained from three grid resolution is also compared with results obtained by Meyer et al. [6]. There is no significant difference in particle acceleration among three grids, lead to choice of medium grid for further simulations.

$$V_{Design} = M_{Design} \times \sqrt{\frac{\gamma}{MW_{gas}} R_U T_e} \tag{1}$$

$$\frac{T_e}{T_0} = \left[1 + \frac{\gamma - 1}{2} M_{Design}^2\right]^{-1} \tag{2}$$

$$\frac{A_e}{A^*} = \frac{1}{M_{Design}} \left[\left(\frac{2}{\gamma + 1}\right)\left(1 + \frac{\gamma - 1}{2} M_{Design}^2\right)\right]^{\frac{\gamma+1}{2(\gamma-1)}} \tag{3}$$

The exit and throat area ratio as well as thermal property of carrier gas determines the Nozzle design Mach number. The exit temperature and accordingly nozzle design speed can be calculated by Eq. 1

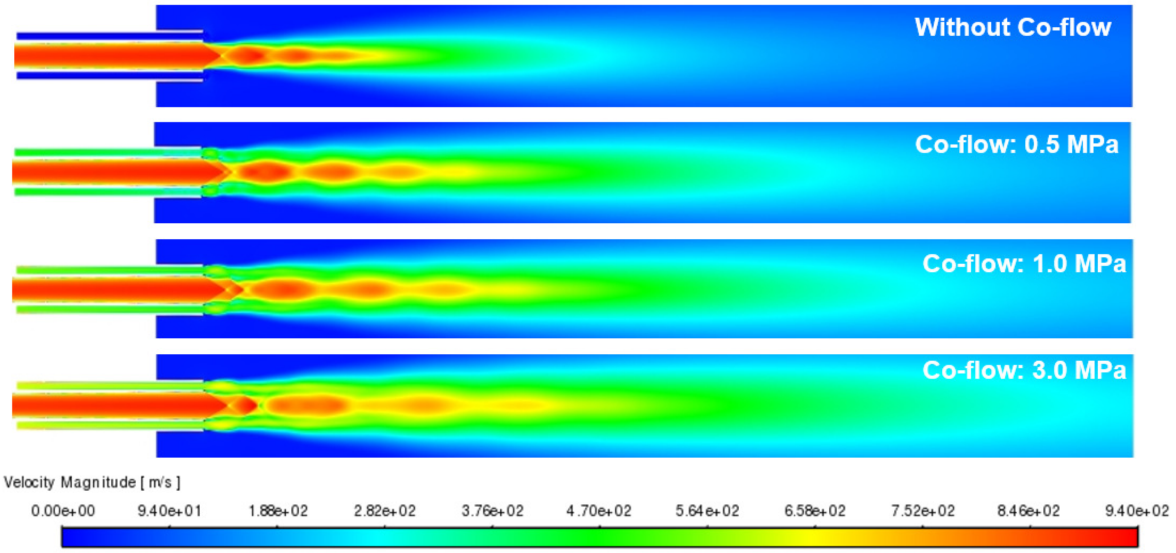


(a) Gas Velocity **(b) Particle Velocity**

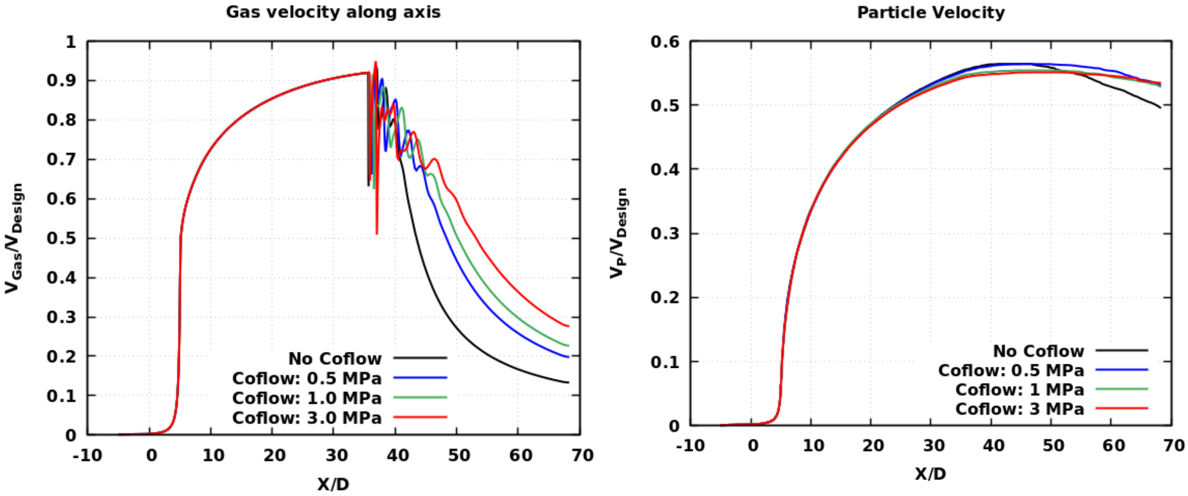
Figure 3. Grid Independence Study (a) Gas Velocity, (b) Particle Velocity

3 Results and Discussions

The traditional cold spray nozzle has circular cross-section, with longer divergent section and exit diameter less than 10 mm. The longer divergence section can lead boundary layer in the nozzle wall interact with the center-line flow and can cause higher friction losses. However, the friction losses can also increase the exit temperature of gas as compare to isentropic design values. Additionally, long length of nozzle requires cleaning multiple time during continuous operations. The proposed co-flow nozzle has been found momentum preserver for central jet flow. There can be many configurations with supersonic central nozzle such as annular subsonic, sonic or supersonic, overexpanded, underexpanded jet. Also, in future the multi-gas with temperature control can provide effective control on particle acceleration, temperature, penetration before impact on substrate. The current study is motivated to provide moving fluid as imaginary wall than a solid wall for particles to accelerate through cold spray system. The below sections discusses the results obtained by axi-symmetric numerical simulations for co-flow effects on particle acceleration through cold spray nozzle. Further, the two shorter nozzles with co-flow are compared by reducing the divergence section length, while keeping the exit and throat cross-section area same, to understand the effectiveness of the co-flow.



(a) Contours of Velocity Magnitude



(b) Gas Velocity

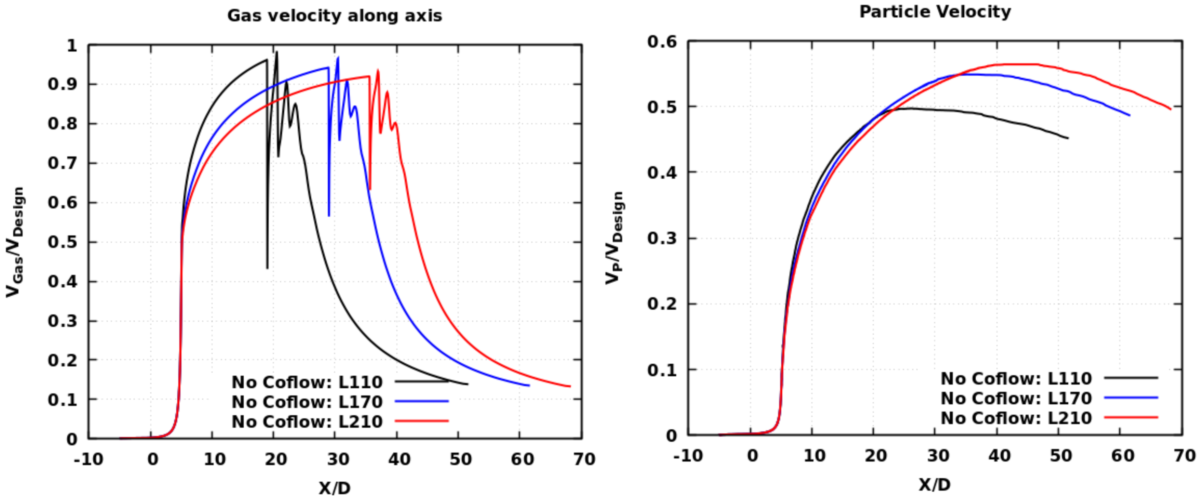
(c) Particle Velocity

Figure 4. (a) Contours of Velocity Magnitude, (b) Axial Gas Phase (c) Axial Particle velocity for no co-flow and various co-flow pressures.

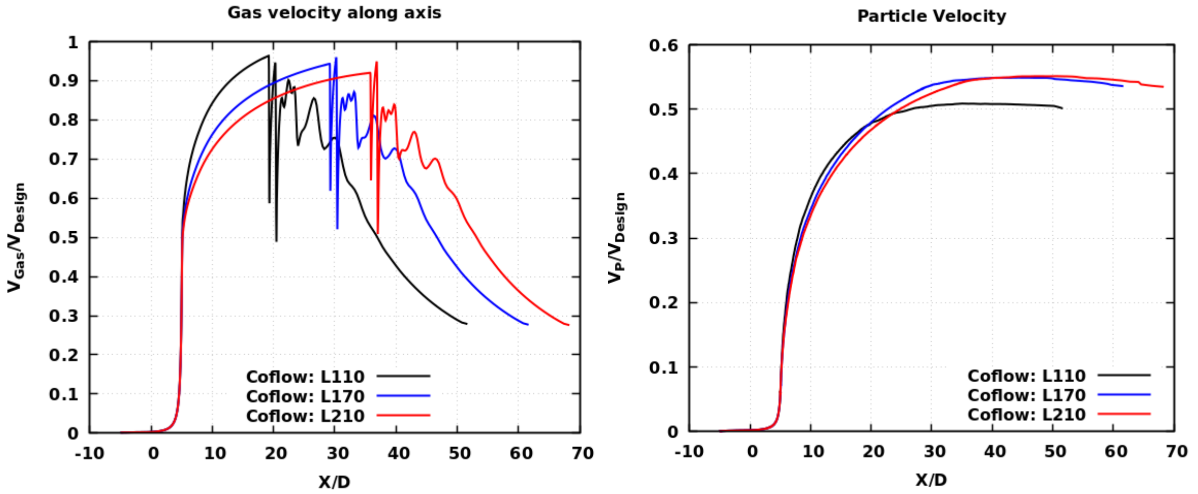
3.1 Effect of Co-flow on cold spray Nozzle

Figure 4a shows the contour plots for velocity magnitude for different co-flow operating conditions, from no co-flow to 3.0 MPa co-flow pressure for nozzle configuration L210 (divergence length = 180 mm). Figure 4b and c, shows the gas phase velocity variation and particle velocity along the axial distances for different co-flow conditions. The without co-flow case clearly captured three shock-cells for 3 MPa operation of cold spray operations. The velocity profile remains unchanged for all four operations before nozzle exit (X/D = 35, in L210 case). However, in presence of co-flow the flow-field significantly changes as supersonic core length increases to longer axial distances. By definition, the supersonic core length can be defined as the axial extent of last shock-cell from nozzle exit. In the current operation, the flow-field is overexpanded based on isentropic relations, however with pressure losses due to thick boundary layer and friction can cause slight reduction in overexpansion. The visibility of clear shock at the lip of the nozzle is visible. The supersonic core length is upto $X/D =$39.8, based on axial gas velocity profile. After supersonic core length, the gas velocity decay rapidly, due to increased mixing due to high entrainment of mass from the surrounding. The particle velocity will reach maximum near the end of supersonic core and starts decreasing after $X/D =$ 45.0. However as the gas velocity decreases rapidly by 85 % before $X/D =$70, the centerline particle speed decreases 12 % along the same axial distance. It is clearly evident from velocity contours that the supersonic core increases with increase in operating co-flow pressure from 0.5 MPa to 3 MPa. Along with supersonic core, the characteristic decay slows down with increase in co-flow inlet pressure. The velocity contours reveals that the co-flow prevents rapid mixing in the supersonic core and elongate the shock-cells in axial direction. The supersonic core length increases to $X/D =$ 44, 46.2 and 49.3, respectively with co-flow inlet pressure 0.5, 1 and 3.0 MPa. The maximum increase in supersonic core length is 23.8 % at co-flow pressure 3 MPa. With co-flow the particle speed reaches maximum at $X/D =$ 45 and remain almost constant up to $X/D =$ 58.0. The decrease in particle velocity along the axis is insignificant as compare to no co-flow case.

3.2 Effect of Divergence Length with co-flow



(a) Gas Velocity: No Co-flow **(b) Particle Velocity: No Co-flow**



(c) Gas Velocity: Co-flow 3 MPa **(d) Particle Velocity: Co-flow 3MPa**

Figure 5. (a) Axial Gas Phase, and (b) Axial Particle velocity for different divergence length of nozzle.

With the observation of maximum increase in supersonic core length as 23.8 %, the shorter nozzle was designed with same exit design Mach number with total length 170 mm (L170 configuration). However, additional reduced length nozzle (L110) was also simulated to understand the contrast in the performance. The same simulations are performed for two shorter nozzle and compared with no co-flow and 3MPa co-flow operating pressure. Figure 5a and b, show the axial plots for gas velocity and particle velocity for no co-flow condition with different divergent length nozzles. As the length of nozzles become shorter, the exit velocity increases from 92 % design velocity for L210 nozzle to 96 % design velocity for L110 nozzle. Apart from divergent section length of nozzle, rest of the flow conditions are same. Hence, the profile, number of shock-cells in the jet flow looks same. In without co-flow case, the particle velocity follow the similar trend, however, smaller divergent section nozzles can reach lower maximum speed than the longer divergent section nozzles. It is reflected that longer nozzle can provide longer residence time for particle to remain in high-speed flow to impart higher speed, while shorter nozzles cannot provide the longer residence time. In Fig. 5c and d, the axial plots are plotted for co-flowing case operated at pressure 3 MPa, same as central nozzle. The supersonic core length increases 2.2 times for L110, while increases 2.8 and 2.9 times for L170 and L210 nozzles. L170 nozzle's supersonic core remains closer for no co-flow L210 nozzle, which suggests that co-flow can enable to reduce divergent section of nozzle. The particle acceleration from L170 co-flow remains closer to L210 with co-flow case and keeps particle speeds almost constant for longer distance. Although the current preliminary study uses same gas from central and co-flow nozzles, it should be kept in mind additional flow stream means addition mass flow rate. The co-flow design can be more practical if different gases are used for both inlets with aim to keep central nozzle operating with Nitrogen or Helium, while co-flow nozzle with air or nitrogen, in respective case. Further understanding of mixing of two different gases through co-flow nozzle may pave the pathway for development of co-flow nozzle for efficient cold spray application.

4 Conclusions

In this numerical study, co-flow nozzle design which has been found in different application to increase the supersonic core length has been investigated for cold spray system. The findings of the study can be summarised as follows:

- The numerical simulations suggested that co-flow operating from lower to same level of central nozzles operating pressure, elongates the supersonic core length significantly as well as reduces the rate of characteristics decay in the jet field by providing a shield to the central nozzle. This leads to particles in centerline of nozzle to preserve momentum even passing through the supersonic core length. There is insignificant particle velocity decay occur in comparison to no co-flow case, where particle velocity decays up to 12%.
- Reducing the divergent section length increases exit gas velocity from nozzle, however, it also leads to reduction in residence time for particle in high-speed stream, which affects negatively and reduces the particle's maximum attainable speed.
- Introduction of co-flow in reduced divergent section nozzle, improves the performance at all the lengths for supersonic core elongation as well as particle acceleration.
- Based on supersonic core-length elongation L170 nozzle performs at par as L210 nozzle with gas velocity, while better in particle acceleration than no-coflow L210 nozzle.

The integration of co-flow nozzle for cold-spray will require further studies on multi-gas operation, optimization of mass-flow rate through the system as well as further develop strategy for particle injection before practical experimentation.

References

[1] R.N. Raoelison, Ch. Verdy, and H. Liao. Cold gas dynamic spray additive manufacturing today: Deposit possibilities, technological solutions and viable applications. *Materials & Design*, 133:266–287, 2017.

[2] M. Kamaraj and V. M. Radhakrishnan. Cold spray coating diagram: Bonding properties and construction methodology. *Journal of Thermal Spray Technology*, 28:756–768, 2019.

[3] S. R. Bakshi, T. Laha, K. Balani, A. Agarwal, and J. Karthikeyan. Effect of carrier gas on mechanical properties and fracture behaviour of cold sprayed aluminium coatings. *Surface Engineering*, 23(1):18–22, 2007.

[4] H. Sharma, A. Vashishtha, P. Lovaraju, and E. Rathakrishnan. Characteristics of sonic and supersonic co-flow jets. 03 2008.

[5] H. Sharma, A. Vashishtha, E. Rathakrishnan, and P. Lovaraju. Experimental study of overexpanded co-flowing jets. *The Aeronautical Journal (1968)*, 112(1135):537–546, 2008.

[6] M. Meyer and R. Lupoi. An analysis of the particulate flow in cold spray nozzles. *Mechanical Sciences*, 6(2):127–136, 2015.

[7] Xinkun Suo, Shuo Yin, Marie-Pierre Planche, Taikai Liu, and Hanlin Liao. Strong effect of carrier gas species on particle velocity during cold spray processes. *Surface and Coatings Technology*, 268:90–93, 2015. 6th Rencontres Internationales de la Projection Thermique.