A concept of Aerospike Nozzle for Cold Spray Additive Manufacturing: towards a potential solution for preventing the issue of clogging

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Abstract

The clogging, a frequent gas passage deformation phenomenon because of powder accumulation on inner nozzle wall, is a major issue in long duration Cold Spray (CS) operations and a major challenge for Cold spray technology to be adopted for additive manufacturing. This study aims to design and integrate new nozzle design in Cold Spray operations for addressing the clogging issues in traditional circular convergent-divergent (C-D) nozzles. The concept of the Aerospike nozzle is proposed for that purpose and is investigated using numerical simulation methods in this paper. An aerospike nozzle allows gases to accelerate externally bounded by environment on one-side and contoured spike wall on other side. After accelerating along the spike wall, aerospike nozzle can generate a longer supersonic gas stream. The spike region can be truncated near the tip to provide a flat face for powder injection. This proposed strategy will allow powder particles to accelerate through a longer supersonic core region, without interacting with nozzle wall. With appropriate operating parameters, an aerospike nozzle can reduce or eliminate the clogging issue completely. The efficiency and operation of aerospike nozzle is compared with same Mach number C-D nozzle using numerical simulations at stagnation pressure of 30 bar and temperature of 623K, where the aluminium powder particles are injected at 30 g/min in the centerline of both nozzles and are accelerated to similar velocities. The powder particles are accelerated in supersonic core region of aerospike nozzle without interacting with nozzle wall, it is concluded that the aerospike nozzle can be a promising nozzle design to provide clogging free long duration CS operations.

Keywords: CFD simulation, Aerospike nozzle, Cold Spraying, supersonic flow, clogging

Introduction

Cold Spray (CS) is a coating deposition method that has been developed in the 20th century. This technique has been experimented with vast improvements and developments to be lately considered as a new additive manufacturing (AM) technique. The additive process can produce a coating or a bulk part without properties changes caused by a thermal process such as in thermal additive processes. Thus, CS enables tremendous flexibilities, in addition to economic benefit thanks to shorter production time [1-3].

CS is a solid-state process, by which the material layers are added on the substrates by means of an acceleration of the feedstock material in the form of micron-sized powder. The accelerating gas reaches supersonic speeds by using a traditional converging–diverging (CD) nozzle [4,5]. The convergent-divergent nozzle uses an inlet high pressure gas (strongly higher than the atmospheric pressure at the nozzle outlet) to produce a high velocity supersonic gas flow. The converging section is generally designed to reach a sonic gas flow at the throat area (minimum cross-sectional area in convergent/divergent nozzle). Then, the gas is expanded to increase the flow velocity at a supersonic speed while expanding through the divergent section of C-D nozzle. The C-D nozzle imparting supersonic flow for CS application, usually designed by assuming flow inside the nozzle as isentropic and using compressible isentropic relations [6].

A recent application of cold spraying is the development of additive routes [7-10], encounters the challenges of high gas mass flow rate requirement as well as nozzle clogging. Both issues can be linked to the nozzle design and operational efficiency of the same in CS system. The high mass-flow rate requirement can be tackled by efficient and optimized nozzle design, which can impart maximum powder particle speed with minimum gas flow rate requirement. The clogging of the conventional nozzles occurs due to the complexity of the gas flow inside the nozzle, influenced by the exit environment [11-13], combined with the complex behavior of the powders inside the nozzle which may be easily heated to be sticked on the inner nozzle wall [14-17]. To overcome the above two challenges, it is required to rethink the nozzle design for Cold spray operations to have efficient and clogging free operations. Amit et al. [18-19] has suggested the use of co-flow nozzle [20] to reduce the divergent section length of traditional C-D nozzle and provide virtual fluid wall around the inner particle laden flow to preserve the momentum of central nozzle region. Taking idea from extensive nozzle performance studies in aerospace propulsion applications [21], the current study aims to investigate the operation of aerospike nozzle for Cold spray application. The aerospike nozzle is considered as annular nozzle, while accelerating the gas along the central curved spike path to supersonic speeds. The spike can be truncated near the tip as shown in Fig. 1, which created a recirculation low-pressure region. The truncated region of spike can be an ideal location for powder particle injection for aerospike operations in CS. The aerospike nozzle is advantageous in aerospace application by providing higher performance than compared to traditional C-D nozzle at different altitude, which can add advantage for Cold spray application to operate in various environments including in vacuum. The next sections of the paper will demonstrate the performance of one of the aerospike nozzle designs and compare it with traditional C-D nozzle for aluminium particle acceleration using axisymmetric numerical simulations.

Aerospike nozzle design

Design parameter of conventional C-D Nozzle:
To design of traditional supersonic CD nozzle is based on the area ratio between exit of the nozzle and throat (minimum cross-section area along nozzle axis) as shown in Eq. 1 [6, 22-24].

$$\varepsilon = \frac{A_e}{A_t} \tag{1}$$

where ε is the area ratio between the nozzle throat and the nozzle exit, A_e and A_t are the areas of the nozzle exit and throat. Considering the gas flow is isentropic, the exit design Mach number of nozzle is dependent on area ratio for a given gas (as shown in Eq. 2):

$$\frac{A_e}{A_t} = \frac{1}{M_e}\left[\frac{2}{(\gamma+1)}\left(1+\frac{(\gamma-1)}{2}M_e^2\right)\right]^{\frac{\gamma+1}{2(\gamma-1)}} \tag{2}$$

where M_e is the exit design Mach number, and γ is the ratio of specific heat of gas. At the nozzle inlet, the flow is subsonic and initial (stagnation) values of pressure (P_0) and temperature (T_0) are assigned at the converging section of the nozzle. The Mach number is then iteratively increased, while the gas characteristics are calculated for each point through the isentropic relationships of (Eq. 3, 4).

$$\frac{T_0}{T} = 1 + \left[{(\gamma-1)}/{2}\right] \times M^2 \tag{3}$$

$$\frac{P_0}{P} = \left[1 + \left[{(\gamma-1)}/{2}\right] \times M^2\right]^{\frac{\gamma}{\gamma-1}} \tag{4}$$

where T_0 is the stagnation temperature at nozzle inlet, T is the temperature at a specific point, P_0 is the stagnation pressure at nozzle inlet, and P is the pressure at a specific point.

Design of the Aerospike nozzle

In Fig. 1, a schematic of aerospike nozzle is shown, where the supersonic gas is expanded externally, with one side fluid boundary and other side contoured spike wall. The contoured spike allows flow, which is coming out of annular region at certain angle to transition smoothly over the spike towards the axial direction near the spike end tip. The contour design of spike is traditionally based on Method of Characteristics (MOC) or MOC in conjunction with stream function evaluation, which can be derived for smooth transition of flow direction with least amount of pressure losses. Based on inlet strategies and design of spike, the aerospike nozzle can be classified as: Circular and Linear aerospike nozzles. Further, the linear and circular aerospike can be further subdivided into 1) Continuous Inlet aerospike or 2) clustered aerospike nozzle, where the continuous one will have single inlet operating pressure and clustered one can be operated with multiple inlet pressures. The design Mach number of aerospike nozzle can be related to throat area and exit area, while these areas can be calculated as below:

$$A_t = \frac{\pi(R_e^2 - R_b^2)}{\sin\delta} \tag{5}$$

$$A_e = \pi(R_e^2 - R_b^2) \tag{6}$$

where R_e is the radius of cowl lip and R_b is the radius of the base in truncated spike nozzle (in case of full spike, $R_b = 0$) A_e and A_t are the cross-section area at the exit and the throat respectively, and δ flow angle at throat plane. The area ratio can be used to calculate the design Mach number of aerospike nozzle.

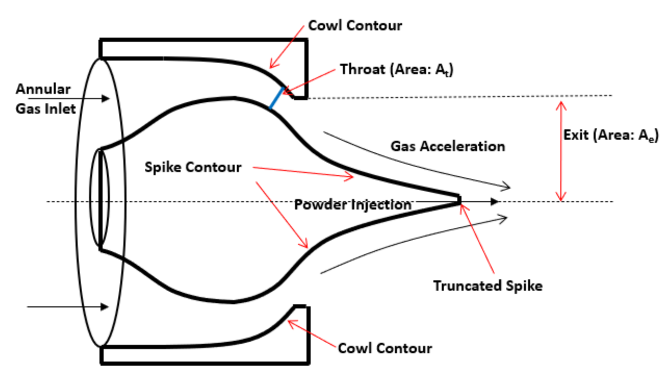


Fig 1. Schematic of IE Aerospike Nozzle and its CS operation

The spike contour can be designed to produce two kinds of aerospike nozzles: external expansion (EE-aerospike, minimum length aerospike nozzle) and internal-external expansion (IE-aerospike nozzle). The EE aerospike nozzle expands all the supersonic flow outside the nozzle annular region on the spike wall, where the throat exists at cowl lip corner. In IE-aerospike (as shown in Fig 1), the supersonic flow will expand with two expansions, one is internal expansion inside the annular region, and another is external expansion, outside the annular region on spike contours. The throat exists inside the annular region for IE-aerospike. In the proposed Cold spray operation with aerospike nozzle, it is planned to inject powder particle in the smaller truncated zone of spike. Because of the minimum length of aerospike, the external expansion nozzle design shows tendency of flow-separation before reaching the spike end for few operations, which may allow poor interaction with injected powder particles near the centerline. On the other hand, IE aerospike nozzle gradually expands the flow to supersonic speeds with longer spike length may be more suitable for CS operations. Hence, IE-aerospike nozzle is designed for current study.

Computational Method

All the numerical simulations are performed by solving two-dimensional axisymmetric Navier-Stokes equations along with RANS turbulence model in Ansys Fluent 2021. The ideal gas assumption is used for nitrogen as process gas. The computational method, model validation and grid independence study are adopted from Amit et al. [19]. This section discusses only computational domain and boundary conditions. The other computational details can be accessed from above mentioned paper.

Computational Domain

In order to compare the traditional convergent-divergent (CD) nozzle for CS operations with the newly designed aerospike nozzle, the long divergent length (189 mm) CD nozzle from Ref. 19 was selected. The IE aerospike nozzle was designed with the same exit Mach number as of circular CD nozzle. The throat radius of the CD nozzle was also used same as annular region of IE Aerospike nozzle while designing it. The maximum outer radius of throat region is 6.07 mm, and the spike length is 19.7 mm, which was truncated at height 0.5 mm along spike contour for powder injection.

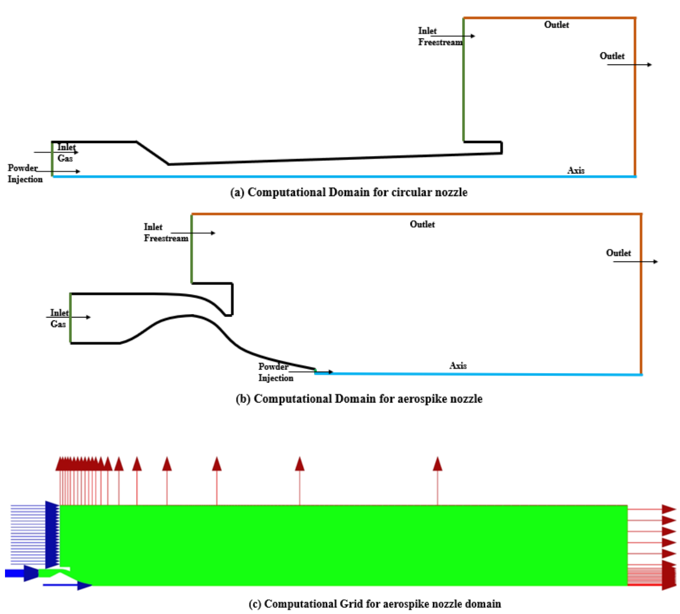


Fig 2. Computational Domain for Circular Nozzle (top) & Aerospike nozzle (middle) & grid for aerospike nozzle (bottom)

The computational domains for circular CD nozzle & IE aerospike nozzle are shown in (Fig 2) along with computational grid for aerospike nozzle. The domain for aerospike is extended up to 200 mm after the nozzle exit, while kept 100 mm in case of circular CD nozzle. Similar grid sizing has been used in aerospike case as it was validated for CD nozzle in Ref 19. The solution approaches a steady state after prescribed number of iterations for given conditions.

Boundary Conditions

Both the nozzles are operated with the stagnation pressure of 3MPa and stagnation temperature of 623 K as pressure inlet condition. At the nozzle exit, the domain was initialized with atmospheric pressure (101.325 kPa), and an ambient temperature (293 K) is prescribed. The domain outlet was modeled as supersonic outlet. The freestream inlet was given a low velocity of 34 m/s to avoid zero velocities in the initialized domain. The center line powder injection is modelled at the inlet of CD nozzle and at the truncated spike region of aerospike nozzle. The aluminium particle of uniform size 25 μm are injected with 30 g/mins for both the nozzles. In circular CD nozzle the powder was injected along with gas at operating stagnation pressure of 3.0 MPa at the inlet plane. However, the powder injection strategy is different in case of aerospike nozzle. As the flow merged and separated from the wall at the truncated spike region near the end of aerospike nozzle, it created recirculation (low-pressure) region. Hence, if the powder particles are injected with high pressure, they may not have sufficient residence time to get affected by outer annular supersonic flow of aerospike. As the vicinity of truncated spike region is at low pressure, a small gas pressure along with powder will be sufficient to inject powder into supersonic stream for momentum exchange and acceleration to supersonic speeds. Hence in the current study, the powder was injected with nitrogen gas at 2 bars at the truncated spike zone.

The powder injection into gas phase is modelled by suing Discrete Phase Modelling (DPM) method. A two-way Lagrangian approach was utilized to simulate particle acceleration with the high-Mach number drag law. The stochastic tracking with discrete random walk (DRW) was used to account for particle dispersion due to turbulence effects.

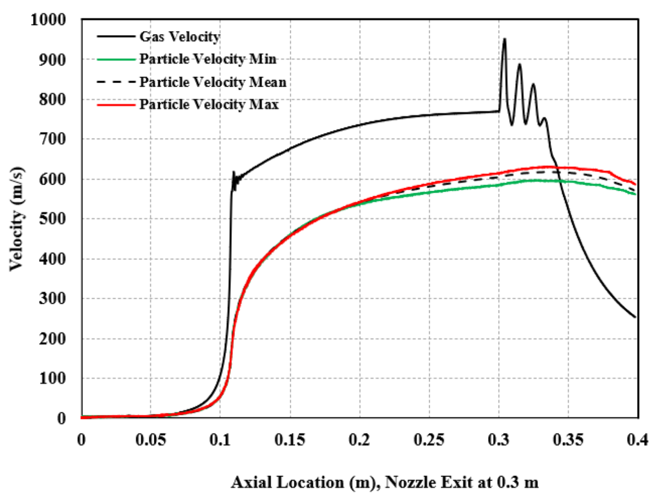
Results and Discussions

The performance of aerospike nozzle has been analyzed by carrying out two-dimensional axisymmetric gas simulation for circular C-D nozzle and discrete phase modelling for 25 $\boldsymbol{\mu m}$ aluminium powder particles injected in centerline. The simulation results are postprocessed for centerline gas velocity for both the nozzles and extracting particle tracks for minimum, mean and maximum velocity achieved by particles. Further, the velocity contours and particle tracks are discussed for flow-field analysis and particle acceleration.

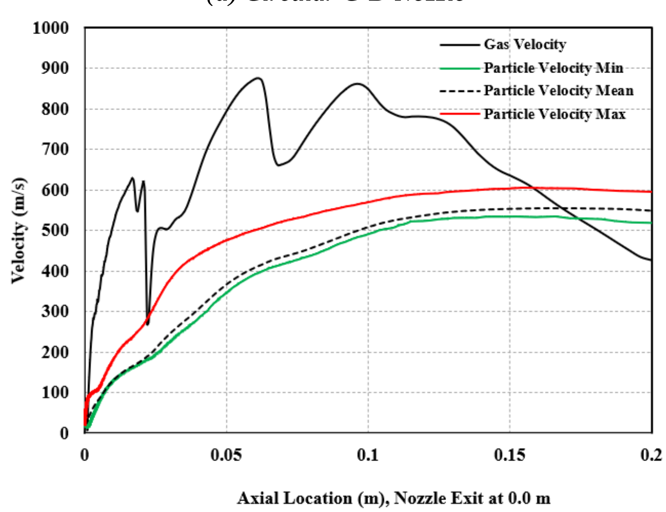
Gas & Particle Axial Velocity Comparison

Figure 3a shows the gas velocity and particle velocity plots along the centerline of circular C-D nozzle. It is to note that C-

D nozzle, convergent section starts at axial location X= 0, throat at X = 0.11 m, while the divergent section ends at X = 0.3 m. The gas acceleration can be seen in Fig. 3a with nozzle design features, where the gas velocity increases along with convergent section and suddenly reaches near Mach = 1 at the throat. After the throat the gas flow further accelerates to supersonic flow up to the end of divergent section. At the nozzle exit, the exit supersonic flow discharges into the 101.325 kPa atmosphere. It will exhibit shock-cells, regions of mixed flow of shock waves and expansion fans, causing oscillation in gas velocity. It is also called supersonic core region. The supersonic core region ends, when the gas velocity becomes subsonic, it will further decay rapidly to lower subsonic speeds due to enhance mixing with the surroundings. The particle injected in centerline of circular C-D nozzle at the inlet, will also accelerate with similar trend as acceleration of gas, but not rapid as gas. The powder particles smoothly accelerate to maximum mean velocity of 618 m/s, at 34 mm after the nozzle exit. The maximum particle velocity was computed as 630.3 m/s, near the similar location. Due to the rapid decay in gas speed, the powder particle speeds may decay after a short axial distance of supersonic core.



(a) Circular C-D Nozzle



(b) Aerospike Nozzle

Fig 3. Gas Velocity Magnitude and Particle Speed (Min, Mean and Max Track) for (a) Central Nozzle & (b) Aerospike nozzle.

Figure 3b shows the gas velocity and particle velocity for particle tracks obtaining minimum, mean and maximum velocities for aerospike nozzle operation. It is to note here that the truncated spike ends at X = 0. The merging flow attached to nozzle spike wall will create a small recirculation zone (size depends on truncation height), and after that the gas speed in the centerline increases rapidly and fluctuates further due to presence of shock-cells. However, the shock-cells are much longer in comparison to circular C-D nozzle. The particle injected into recirculation zone from truncated spike will rapidly attain high velocity and maintain their speed for longer distances due to presence of longer supersonic core length. The powder particle attains maximum mean velocity of 554 m/s at X= 163 mm after the spike end, while the maximum local particle velocity achieved is 606 m/s. The momentum exchange between gas and powder particle occurs mainly in the supersonic core region of gas flow in aerospike nozzle, while the particle accelerates in divergent section of circular C-D nozzle, and it maintains speed in supersonic core region. The powder particles in aerospike nozzle do not interact with nozzle wall only interact with fast moving gases, which may eliminate the issues of clogging for long duration operations of CS system with aerospike.

Gas Velocity Contours & Particle Tracks

Figure 4 shows the velocity contours for circular C-D nozzle and aerospike nozzles, with zoomed in spike region for aerospike nozzle. The circular C-D nozzle exhibits the typical supersonic jet structures with flow exiting at supersonic speed from the nozzle exit and forming three shock-cells before rapidly decaying to lower velocities within 100 mm after the nozzle exit. However, the aerospike nozzle exhibits different flow structures than the circular C-D nozzle. The zoomed view of flow acceleration within the annular aerospike region shows the internal expansion near the throat of aerospike and external expansion on the spike wall, leading to supersonic flow acceleration within the spike region of aerospike nozzle. Further after the spike, large shock cells (mixed subsonic and supersonic flows) are observed up to X = 0.16 m distance. The first shock cell, extends up to X = 0.03 m and the second shock cell ends up to X = 0.072 m. The overall supersonic core ends up to X = 0.16 m. The particle rapidly accelerates in the first and second shock-cells and further maintains speed for longer axial distances in aerospike nozzle CS operations. The particle tracks are shown in Fig. 5. The particle tracks for circular C-D nozzle shows continuous acceleration of powder particles from convergent inlet region to throat and further rapid increase in particle velocity, while crossing the throat and continuous increase up to nozzle exit and end of supersonic core length outside nozzle. The particle tracks for powder injected at the truncated spike surface in aerospike nozzle, shows wavy pattern of dispersion and accumulation within the first shock-cell, and further increase in particle velocity in subsequent shock-cells.

From the above discussion, it is evident that the particle acceleration in aerospike nozzle for proposed operations occurs in supersonic core region, hence, the residence time of particle within the core region is important. If the powder particles are injected at higher pressure at the truncated spike surface, it may be very much possible that the particle may have very short residence time within the shock-cells and particle speed may not be affected by annular aerospike gas flow. Another important aspect of the aerospike nozzle operation is that the annular throat region of aerospike nozzle will have higher cross-section area (of same throat dimension), which will end-up in higher gas flow rate in the aerospike nozzle operations. The C-D nozzle operates at 14 g/s nitrogen flowrate, while aerospike operates at 163 g/s nitrogen gas. The change in mass-flow rate corresponds to the throat area difference between both the nozzles. As the central injection of powder particle at truncated aerospike nozzle can eliminate the issue of clogging, the careful optimization of aerospike nozzle design and operations are further required to optimize the clogging free operations with efficient gas flow rate in future studies.

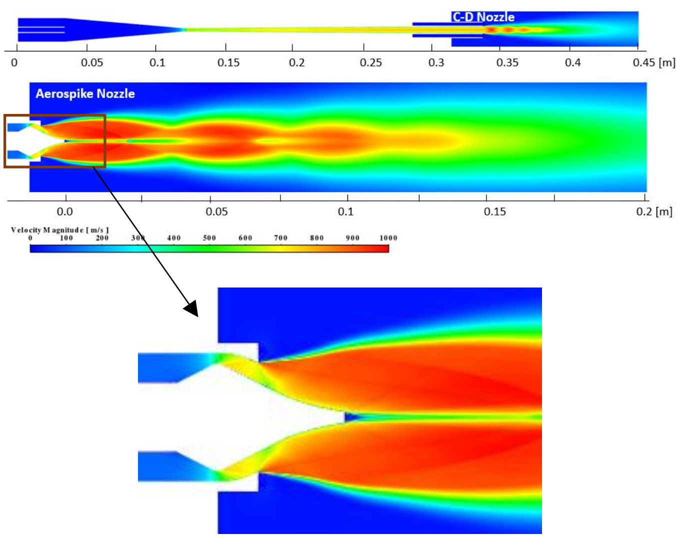


Fig 4. Gas Velocity Magnitude comparison for Central Nozzle & Aerospike nozzle.

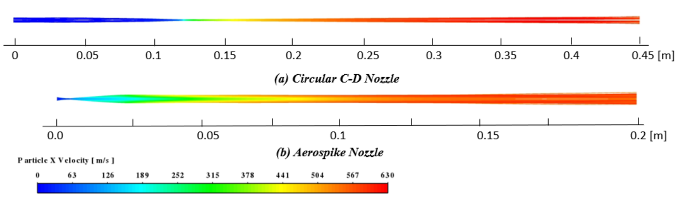


Fig 5. Particle Tracks for (a) Central Nozzle & (b) Aerospike nozzle.

Conclusion

This paper investigates a potential solution against the issue of clogging to which cold spray operations suffer from frequently in additive manufacturing applications. A long duration CS operation can lead to powders accumulation on the nozzle walls when they are exposed to a high temperature inside the convergent zone of the conventional cold spray nozzles. To prevent such an event, an idea of two separate gas flow was envisioned by considering the concept of aerospike nozzle. The similar operations of circular C-D nozzle and aerospike nozzles, suggests achieving similar Al powder particle velocity with different mechanisms of particle acceleration. The circular C-D nozzle accelerates the powder particle across the throat and in the divergent section, while powder particle injected at the truncated spike region with far lower gas pressure, accelerates within the longer supersonic core regions (the shock-cells). The aerospike nozzle accelerated the gas flow to supersonic speed while expanding to one side to open atmosphere and other side of spike's contoured wall. During the proposed operation of aerospike nozzle, the powder particles do not interact with the nozzle walls, which eliminates the possibility of nozzle clogging. However, the annular design of aerospike nozzle leads to a higher mass flow rate in comparison to same Mach number and throat dimension circular C-D nozzle. The further optimization strategies and studies are required in future to utilize optimum gas flow rate for accelerating powder particles for long duration without clogging operations with aerospike nozzle.

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