Study of a Cold Spray Nozzle Throat on Acceleration Characteristics via CFD

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Abstract. Cold spray technology can obtain coatings in a solid state, suitable for deposition protection, repair, and additive manufacturing. In order to further expand the application areas of cold spraying nozzles, especially the inner surface of the components or areas where a Straight-line conical nozzle cannot be applied, because the study of the throat of the nozzle with the angle will directly reduce the total length of the nozzle (the horizontal direction), hence, the spray with the angle will show its advantage. This study discusses the influence of the throat structure of the conical cold spray nozzle on the acceleration characteristics, including the throat's size, length, and angle. The results show the following. Firstly, under the premise of keeping the shrinkage ratio and divergence ratio unchanged at normal temperature, the throat diameter is between 2–6 mm in size, and the maximum growth rate exceeds 20 m/s. When the throat exceeds 6mm, the growth rate of the outlet slows down, and the growth rate is only 8 m/s. Secondly, the length of the throat has little effect on the acceleration characteristics, the total range fluctuated from 533 to 550 m/s, and 11 mm length of the throat is the closest to 0mm. Additionally, the 90° throat angle has the least effect on the acceleration characteristics. Finally, the particle trajectory is affected by inlet pressure, injection pressure, particle size, and other factors.

Keywords: cold spray technology, nozzle, acceleration characteristics, particle trajectory.

1 Introduction

Cold spraying technology [1] is an emerging technology. Based on the theory of aerodynamics and fluid mechanics, it produces a process of high-speed collision with substrate and formation of a coating, which is mainly applied for surface repair and protection of coating, or additive manufacturing applications [2, 3]. The cold spray nozzle has essential significance for particle acceleration, and throat structure is the key link in the whole nozzle structure.

In the current study, cold spray nozzle structures are linear conical nozzles or straight pipe ladder nozzles, for example, in order to facilitate the spraying of the inner surface of the part, Li [4] studied a nozzle with a total length of less than 70 mm, but many components require a smaller size on the inside surface to be sprayed. Wu [5] added a straight pipe with the same diameter as the outlet at the nozzle outlet to prevent the powder from dispersing, but this nozzle is more suitable for external surface spraying. In order to facilitate the processing and manufacturing, some nozzles processed the expansion section into a straight pipe ladder type. It can effectively spray aluminum, and zinc powder [6], the expansion section of this nozzle is generally longer, so it is more used for external surface spraying. If it is necessary to spray the inner surface of the component or areas where a linear nozzle cannot be applied, spray with the angle will show its advantage. Thus the application of the nozzle is further expanded. However, the throat structure with an angle has rarely been studied.

Hence, this present study aimed to research the nozzle with angles and facilitate spraying in a specific space, e.g., the inner surface repair of components or the straight-line nozzle can not reach the place to spray.

2 Research Methodology

The following formula determines the initial model (Figure 1), then three-dimensional modeling, boundary condition setting, and numerical simulation are carried out to study the influence of nozzle throat on the acceleration characteristics.
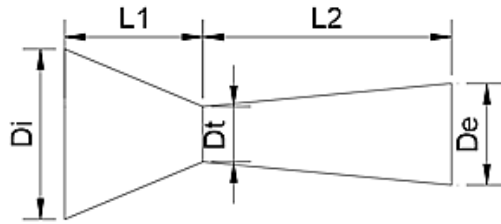
Figure 1 – Initial model

The typical calculation technics is based on the following equations:

$$C = \sqrt{rRT} \ ; \tag{1}$$

$$Ma = \frac{V}{C}; \tag{2}$$

$$Ma = \sqrt{\frac{2}{\gamma-1}\left[\left(\frac{P_i}{P_e}\right)^{\frac{\gamma-1}{\gamma}} -1\right]} \ ; \tag{3}$$

$$\frac{A_e}{A_t} = \left(\frac{1}{Ma}\right)\left[\left(\frac{2}{\gamma+1}\right)\left(1+\frac{\gamma-1}{2}Ma^2\right)\right]^{(\gamma+1)/[2(\gamma-1)]} \ ; \tag{4}$$

$$C_P = \frac{rR}{r-1}; \tag{5}$$

$$T_T = T_i + \frac{V_i^2}{2C_P} \ ; \tag{6}$$

$$p_T = P_i\left(\frac{T_T}{T_i}\right)^{\frac{r}{r-1}} \ ; \tag{7}$$

$$\rho_T = \frac{P_T}{RT_T} \ ; \tag{8}$$

$$q_{mcr} = A_t\left(\frac{2}{r+1}\right)^{\frac{r+1}{2r-2}}(rp_T\rho_T)^{\frac{1}{2}} \ ; \tag{9}$$

$$A_i = \frac{q_{mcr}}{\rho_i V_i} \tag{10}$$

$$L_1 = \left(\frac{D_i - D_t}{2}\right)\cot\left(\frac{\alpha}{2}\right); \tag{11}$$

$$L_2 = \left(\frac{D_e - D_t}{2}\right)\cot\left(\frac{\beta}{2}\right), \tag{12}$$

where C – the ideal speed of sound; γ – is the specific heat ratio of gas; R – the gas constant; T – the ambient temperature; Ma – the Mach number; Pi – the inlet pressure; P_t – the throat pressure; $P_e = 1.01\cdot10^5$ Pa – the outlet pressure; q_{mcr} – the mass flow rate, P_T – the stopping pressure; $V_i = 30$ m/s – velocity; ρ_T – the stopping density, T_T – the stopping temperature; C_p – the specific heat capacity of constant pressure.

According to the calculation, the contraction ratio is about 3.0; the divergence ratio is about 1.84; $D_i = 12.3$ mm. According to the empirical value [7, 8], the angle of the contraction section $\alpha = 30-60°$, and the angle of the diffusion section $\beta = 0-12°$. According to formulas (11) and (12), $L_1 = 7.2-15.5$ mm, and $L_2 \geq 17.8$ mm can be obtained for the length of the conical cold spray nozzle's diffusion section. Literature shows that the longer the diffusion section is, the faster the acceleration effect is [7]. Hence, $L_1 = 10$ mm, and $L_2 = 60$ mm are taken. Similarly, all parameters are shown in Table 1.

Table 1 – Cold spray nozzle parameters

Parameter	Values, mm							
D_i	6	9	12	15	18	21	24	27
D_t	2	3	4	5	6	7	8	9
D_e	3.7	5.5	7.4	9.2	11.0	12.9	14.7	16.6
L_1	10							
L_2	60							

3 Results and Discussion

3.1 The influence of throat structures

The one-dimensional isentropic analytical model is a convenient tool for roughly estimating the flow characteristics inside a cold spraying nozzle, but the accuracy of predicting the flow and particle velocity outside the nozzle cannot be guaranteed. With the rapid development of computer technology, the computational fluid dynamics (CFD) model has attracted more and more attention due to its high prediction accuracy and feasibility of simulating different situations [9].

The numerical simulation results are presented in Figure 2.

As shown in Figure 2, the maximum growth rate is more than 20m/s between 2–6 mm. When the throat exceeds 6mm, the growth rate of the outlet slows down, and the growth rate is only 8–10 m/s. Therefore, the throat diameter was determined to be 6 mm.

Further study the throat length factor, the effect of throat length on acceleration characteristics was studied with the throat length is 1–15 mm (odd), respectively. Numerical results show that the throat length has little influence on the acceleration characteristic (Figure 3 a). The overall range fluctuates from 533 to 550 m/s. Simultaneously, the temperature has a positive influence on the acceleration characteristic (Figure 3 b).

Finally, in order to facilitate the analysis of nozzle throat angle, the throat length size of 11 mm was selected. The effects of throat angles of 90°, 60°, and 45° on the acceleration characteristics were studied. The results show that the angle of 90° has an advantage on acceleration characteristics (Figure 3 c).
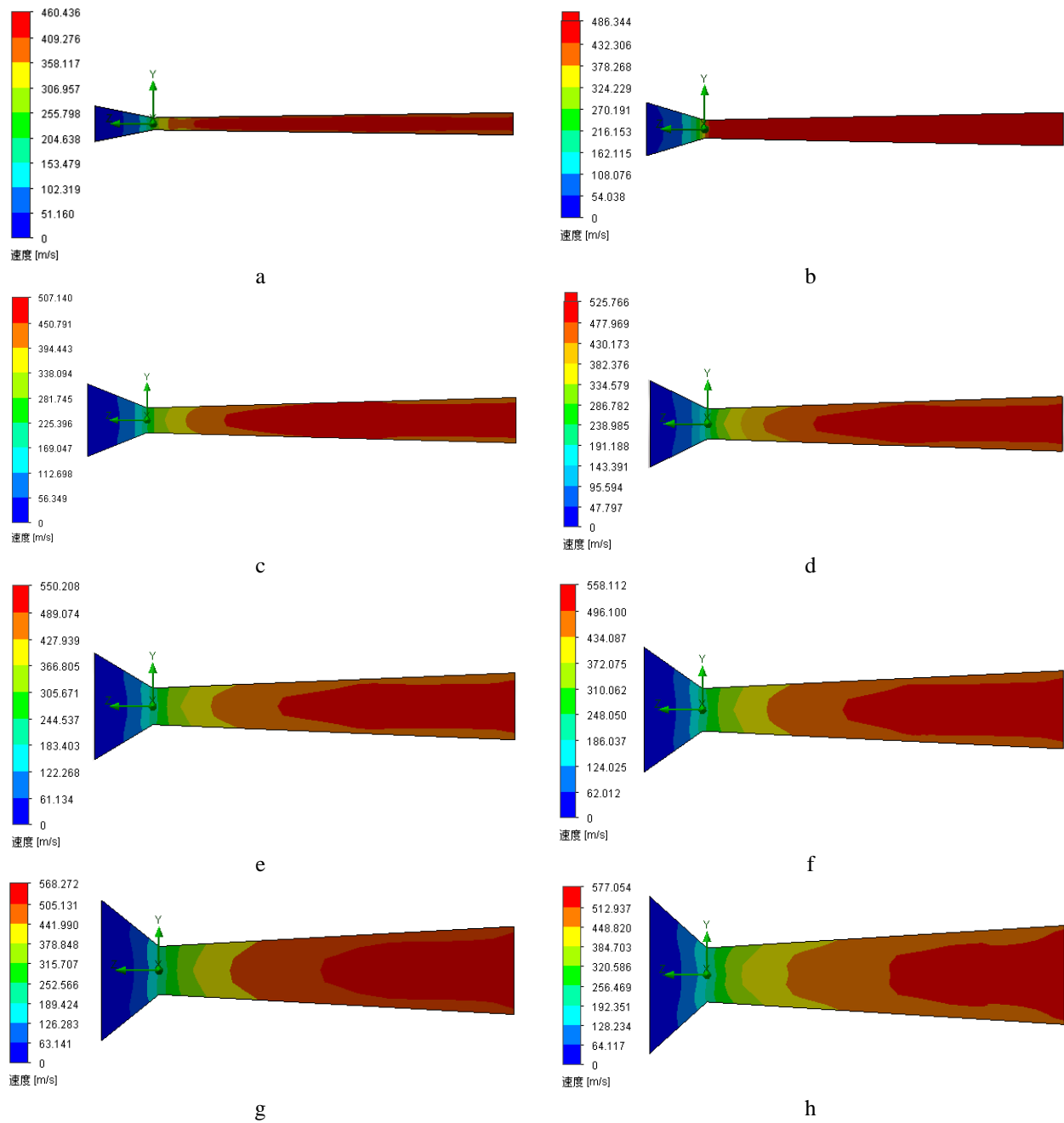
Figure 2 – Nozzles with different diameters of throat: a) 2 mm, V_{max} = 460 m/s; b) 3 mm, V_{max} = 486 m/s; c) 4 mm, V_{max} = 507 m/s; d) 5 mm, V_{max} = 526 m/s; e) 6 mm, V_{max} = 550 m/s; f) 7 mm, V_{max} = 558 m/s ; g) 8 mm, V_{max} = 568 m/s; h) 9 mm, V_{max} = 577 m/s

In this study, the 60 mm length of L_2 is selected. If it is necessary to spray in a specific small area, L_2 can be shortened to the required size. Based on this, the structure can be further optimized according to the actual application situation. Although the main factors affecting the impact velocity of powder include propelling gas, particle characteristics, spraying distance, and length of expansion section [10], the throat structure directly affects the acceleration characteristics of the fluid. Sequentially, it affects the deposition characteristics of powder, and the Computational Fluid Dynamics (CFD) method can give researchers a good reference.

3.2   Particle trajectories

There are many factors influencing the acceleration characteristics of particles, including propulsion gas, temperature, pressure, other factors, and the material properties of particles themselves (i.e., size and shape). Nozzle materials, such as low thermal conductivity, the small heat loss of airflow and particles, are conducive to improving the velocity of particles. However, too high a temperature will cause throat blockage [11].
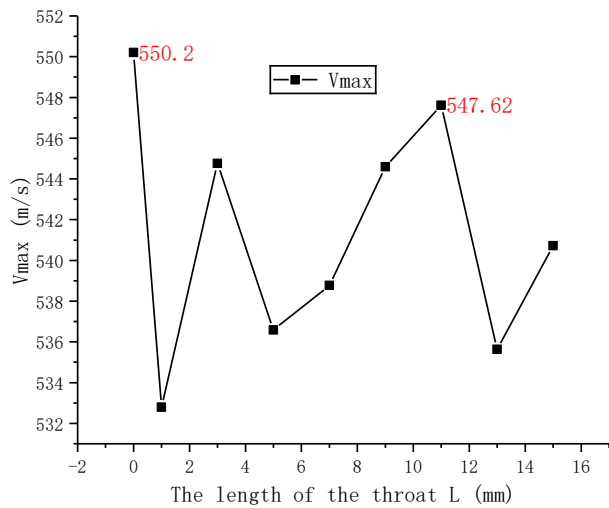
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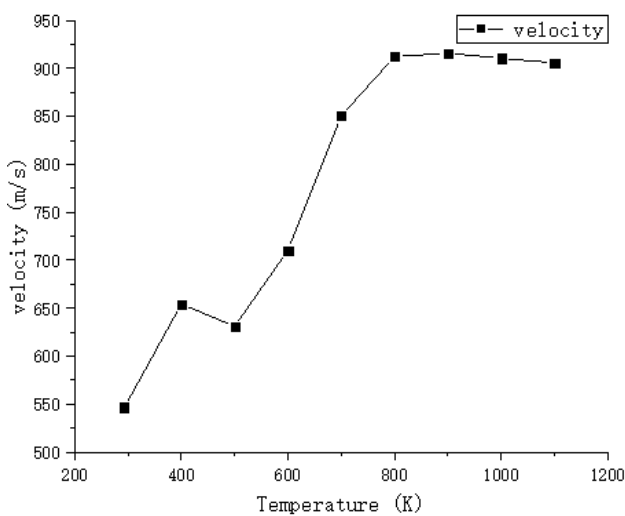
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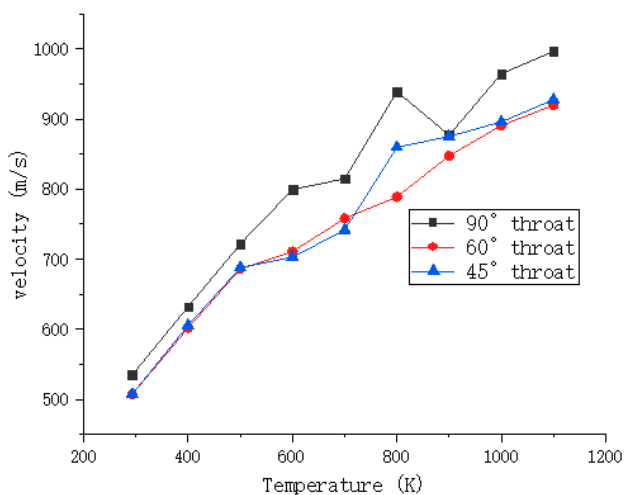
c

Figure 3 – Different factors influence the summary of outlet velocity: a – different nozzle throat lengths; b – different temperatures; c – different angles of throat

Therefore, the injector was set at the boundary between the throat and the expansion section in this study. Studies show that [12], when the particle flow diameter is greater than 15 μm, the wall attachment effect disappears, the particle flow is mainly affected by inertia, and the influence of the airflow field on the final trajectory of the particle flow is small. However, the particle diameter is too large, particle collisions with inner nozzle surface basically affect the acceleration characteristics. This chapter utilizes the titanium particles 20 μm in diameter, aluminum particle 30 μm, copper 15 μm, for no angle of nozzle, injection particles nozzle should not be too great pressure, will lead to particle collision on the wall directly, cause energy loss, pressure is too small can't injection, hence, the injection pressure is 1.1 MPa. The other 90° angle throat structure is 1.6 MPa. The results show in Figure 4.

As a result, the trajectory of the particles by the inlet pressure, powder injection pressure, and the combination of factors such as particle size. In addition, the low particle velocity in Figure 5, the main reason is that the initial velocity value and temperature are low.

As Figure 5 b shows, aluminum particles can obtain effective deposition under the collision condition of 400 °C, but the deposition speed of copper particles cannot meet the requirements of deposition. In this case, the parameter of increasing temperature can be considered (Figure 3 b) because the more initial temperature rise, the higher the speed of fluid and particle, and when the temperature of the particles increases (within the melting temperature), the critical velocity will decrease (Table 2), and the effective deposition will be finally achieved. The same can be done with titanium particles or Ti6Al4V material particles [13–15].

4 Conclusions

The Solidworks/Flow numerical simulation can well predict the acceleration characteristics of the nozzle. Some reference values were obtained by numerical analysis of the cold spray nozzle.

By analyzing the throat with 2–9 mm diameter, the fluid acceleration effect is better within 6 mm. For every 1mm increase in the throat, the velocity increases by about 20 m/s. However, beyond 6 mm, the acceleration becomes slow, and the speed increase is no more than 10 m/s. Throat length has little effect on acceleration characteristics, the total range fluctuated from 533 m/s to 550 m/s, and the 11 mm length of the throat is the closest to zero. The temperature has a promoting effect on the acceleration of the nozzle. In a particular range, the outlet velocity has a linear relationship with the temperature. When the temperature reaches 800 K, the exit speed exceeds 900 m/s.
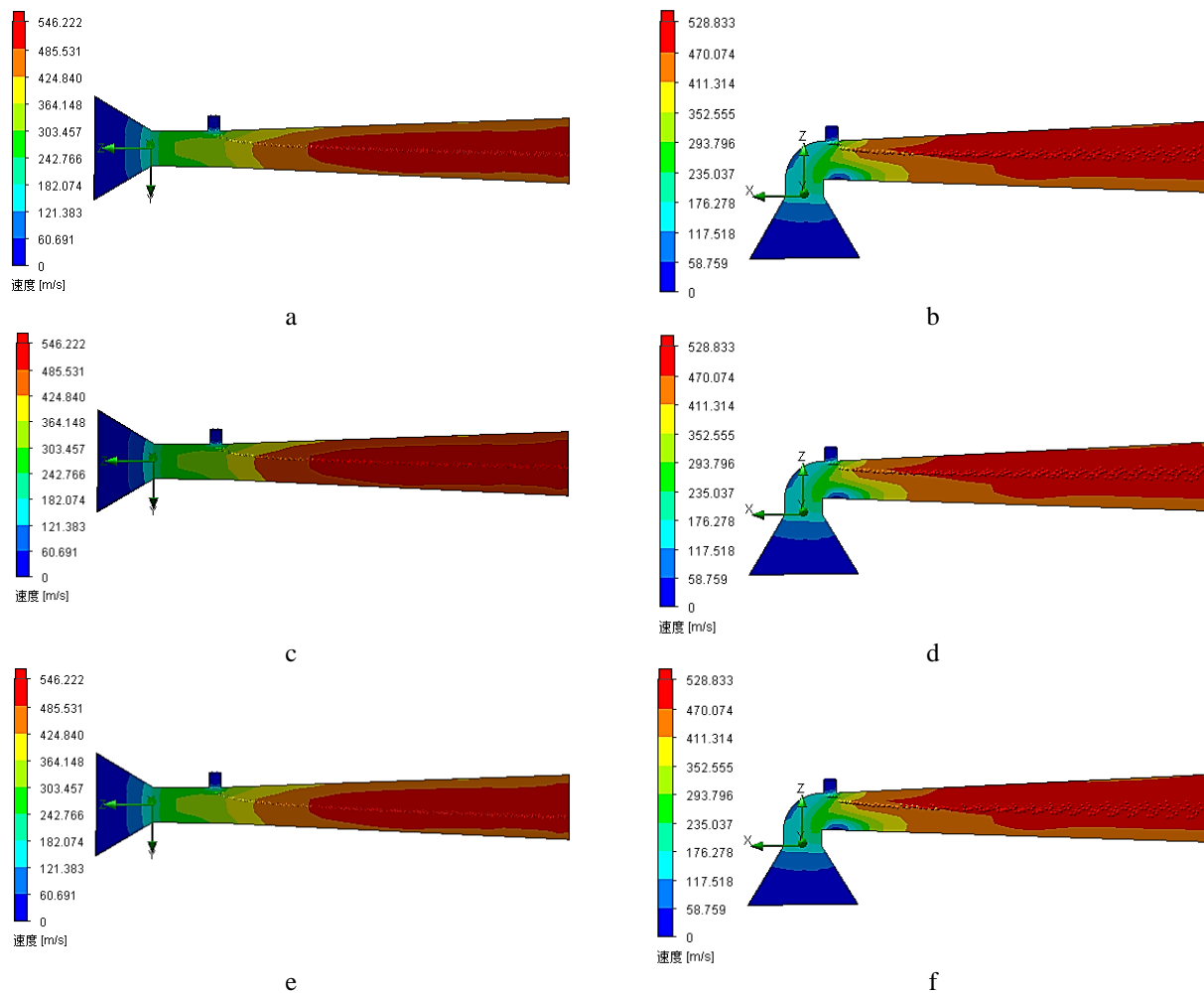
Figure 4 – Optimal conditions for particle trajectories with different throat structures:
a, b – 20 μm titanium powders; c, d – 30 μm aluminum powders; e, f – 15 μm copper powders
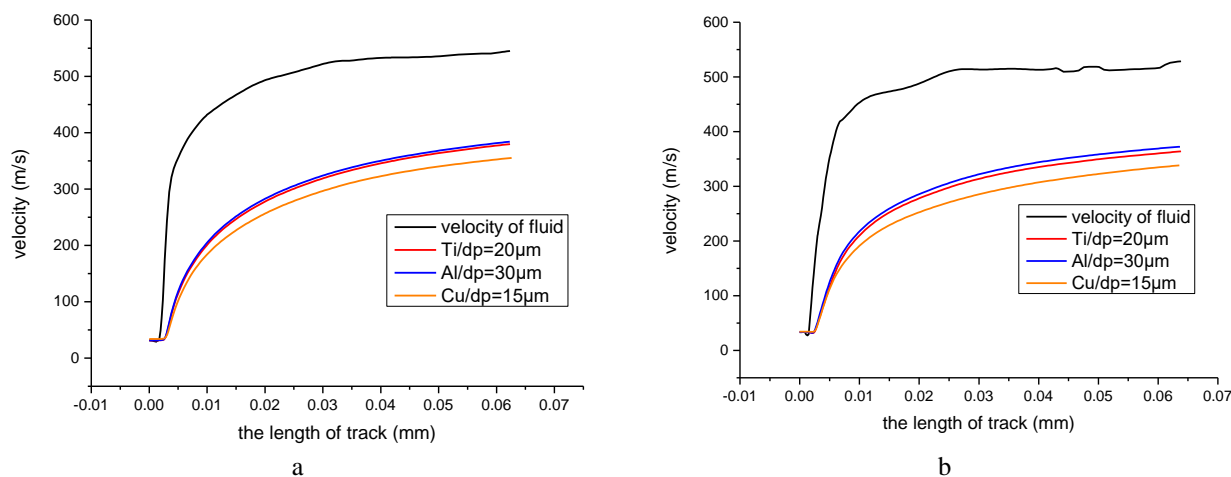

Figure 5 – Different powders and flow velocities: a - without angle; b - 90° nozzle

Table 2 – Critical velocities at different material impact temperatures, m/s

Material	25°C	200°C	300°C	400°C	500°C	600°C	700°C	800°C	900°C
Titanium	719	662	627	590	546	507	460	408	348
Aluminum	630	488	384	239	–	–	–	–	–
Copper	532	465	421	372	316	248	151	–	–

Through the numerical simulation without angle, 90°, 60°, and 45°, it is found that the 90° throat has advantages over 60° and 45°. Compare to no angle nozzle, the 90° throat only reduces the speed of the outlet by 17.4 m/s, which only affects 3 %. Thus, it can be considered that the 90° throat has little influence on the acceleration characteristics. Considering the factors of different material densities, the selected 20 μm titanium powder, 30 μm aluminum powder, and 15 μm copper powder have roughly the same path in the 90° nozzle. If considering the powder of equal diameter, there is a difference in the particle trajectory.

Considering that 90° throat has little influence on acceleration characteristics, it is suggested that in further research, size optimization can be carried out according to the application situations of actual components, and the length of single direction can be optimized, which will expand the application area of cold spraying nozzle.

References

1. Assadi, H., Gartner, F., Stoltenhoff, T., Kreye, H. (2003). Bonding mechanism in cold gas sparing. *Acta Materialia*, Vol. 51, pp. 4379–4394, doi: 1016/S1359-6454(03)00274-X.

2. Hu, W. J., Sergii, M., Tan, K., Shorinov, O., Cao, T. T. (2020). Surface repair of aircraft titanium alloy parts by cold spraying technology. *Aerospace technic and technology*. Vol. 163, pp. 30–42, doi: 10.32620/aktt.2020.3.04.

3. MacDonald, D., Fernandez. R., Delloro. F., Jodoin. B. (2017). Cold spraying of Armstrong process titanium powder for additive manufacturing. *Thermal Spray Technol*, Vol. 26, pp. 598–609, doi: 10.1007/s11666-016-0489-2.

4. Li, W. Y., Li, C. J. (2005). Optimal design of a novel cold spray gun nozzle at a limit space. *Thermal Spray Technology*. Vol. 14, pp. 391–396, doi: 10.1361/105996305X59404.

5. Wu, Z. L. (2011). *Numerical Simulation Research of the Internal Flow Field Cold of the Spray Gun Nozzle and Structural Optimization*. Henan Polytechnic University.

6. Canales, H., Litvinov, A., Markovych, S., Dolmatov, A. (2014). Calculation of the critical velocity of low pressure cold sprayed materials. *Aircraft Design and Manufacturing Issues*, Vol. 3, pp. 86–91. Available online: http://nbuv.gov.ua/UJRN/Pptvk_2014_3_11.

7. Li, Q. (2008). *Structure Design and Optimization of Cold Spray Gun*. The Shenyang University of Technology. Available online: http://cdmd.cnki.com.cn/article/cdmd-10142-2008203950.htm.

8. Wenya, L., Changjiu, L. (2005). Optimal design of a novel cold spray gun nozzle at a limited space. *Journal of Thermal Spray Technology*, Vol. 14, pp. 391–396. doi: 10.1361/105996305X59404.

9. Shuo, Y., Meyer, M., Wenya, L., Hanlin, L., Lupoi, R. (2016). Gas flow, particle acceleration, and heat transfer in cold spray: A review. *Journal of Thermal Spray Technology*, doi: 10.1007/s11666-016-0406-8.

10. Alhulaifi, A. S., Buck, G. A. (2014). A simplified approach for the determination of critical velocity for cold spray processes. *Journal of Thermal Spray Technology*, Vol. 23, pp. 1259–1269, doi: 10.1007/s11666-014-0128-8.

11. Congcong, C., Wenya, L., Tianpeng, H., et al. (2019). Simulation study on effect of cold spray nozzle material on particle. *Journal of Netshape Forming Engineering*, Vol. 6, pp. 149–53.

12. Zhang, Y. J, Liang, Y. L, Zhang J. B. (2011). Numerical simulation of particle tracks in the cold gas dynamic spraying process. *Baosteel Technology*, Vol. 5, pp. 12–16, doi: 10.3969/j.issn.1008-0716.2011.05.003.

13. Sunday, T. O., Jen, T. C. (2019). A comparative review on cold gas dynamic spraying processes and technologies. *Manufacturing Rev*, Vol. 25, pp. 1–20, doi: 10.1051/mfreview/2019023.

14. Pelletier, J. L. (2013). *Development of Ti-6Al-4V Coating onto Ti-6Al-4V Substrate Using Low Pressure Cold Spray and Pulse Gas Dynamic Spray*. The University of Ottawa. Available online: http://dx.doi.org/10.20381/ruor-4265.

15. Jin, L., Cui, X. Z., Ding, Y. F., Zhang, L., and Su, X. D. (2017). Critical deposition velocity calculations and properties investigations of TC4 cold spray coatings. *Surface Technology*, Vol. 46, pp. 96–101, doi: 10.16490/j.cnki.issn.1001-3660.2017.08.016.