NUMERICAL MODELING
OF MICROPARTICLE ACCELERATION IN A LAVAL NOZZLE
WITH SUBSEQUENT DECELERATION IN A WALL COMPRESSION LAYER

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Introduction
There are many ways of coating products, one of which is the method Cold Spray Technology (CST). The uniqueness of the method is that the temperature of particles during CST may be significantly less than their melting point. Therefore CST method can be used not only for coating, but also to create of a given spatial structure. However, due to deceleration particles in the compressed layer near the target, there is a problem when used on CST particles with a diameter of less than a few microns. One way to solve this problem is to use of Laval nozzle with linear order of several millimeters (Laval mini-nozzle). Below are the results of theoretical studies accelerate particles in the micron size Laval mini-nozzle in the method of CST.

Problem statement
We consider the problem on numerical simulation of microparticle acceleration in an axisymmetric Laval nozzle followed with subsequent deceleration of the particles in a wall compression layer. The computational domain is shown in Fig. 1, a. The Laval nozzle was assumed to have the following parameters: outlet radius $R_e = 0.5$ mm, throat radius $R_\ast = 0.26$ mm, supersonic length $z_e - z_\ast = 16.5$ mm, and nozzle exit-to-wall separation $z_w - z_e = 3.3$ mm. For the uniform air flow fed to the nozzle inlet the following parameters were adopted: pressure $p_0 = 2.7$ MPa., temperature $T_0^\gamma = 500K$, adiabatic exponent $\gamma = 1.4$. Aluminum microparticles were injected into the flow at the inlet to the nozzle uniformly over a circular region $r < r_0, r_0 = 0.2$ mm. The velocity and temperature of the injected particles were respectively $u_0^\phi = 5$ m/s and $T_0^\phi = 278 K$. The upper boundary of the region with the jet emanating from the nozzle was located far enough from the jet axis ($R_0 = 10$ mm) so that to exclude the influence of flow perturbations induced by the upper boundary on the flow quantities near this axis. At the nozzle walls and at the axis, impermeability condition and elastic reflection condition were adopted for the gas flow and for the particles, respectively. At the obstacle ($z = z_w$), wall impermeability condition was assumed for the gas flow, with all particles being absorbed there by the obstacle. To calculate the gas-particle flow, a continual-discrete model of [1, 2] was employed, with the model of dusted flow adopted for the gas flow and collisionless kinetic equation used to predict the particle motion

\[
\frac{\partial \varphi}{\partial t} + \frac{\partial F}{\partial z} + \frac{\partial G}{\partial r} + H = 0, \quad \rho = (\gamma - 1) \rho E, \quad e = \rho (E + (u^2 + v^2)/2), \quad E = CT_{1},
\]

\[
\varphi = \begin{pmatrix} \rho \\ \rho u \\ \rho v \\ \rho/ \end{pmatrix}, \quad F = \begin{pmatrix} \rho u \\ \rho u^2 + p \\ \rho uv \\ u(e + p) \end{pmatrix}, \quad G = \begin{pmatrix} \rho v \\ \rho uv \\ \rho v^2 + p \\ v(e + p) \end{pmatrix}, \quad H = \begin{pmatrix} \rho v/r \\ \rho uv/r - F_z \\ \rho v^2/r - F_r \\ v(e + p)/r - uF_z - vF_r - \Phi \end{pmatrix},
\]

\[
\frac{\partial f}{\partial t} + u_2 \frac{\partial f}{\partial z} + v_2 \frac{\partial f}{\partial r} + \frac{\partial a_f}{\partial u_2} + \frac{\partial a_f}{\partial v_2} + \frac{\partial a_f}{\partial T_2} = 0, \quad f = f(t, z_2, r_2, u_2, v_2, T_2), \quad m_2 = \int V_\rho f dV,
\]

\[
dV = du_2 dv_2 dT_2, \quad V_p = 4\pi r_p^3/3, \quad m_1 + m_2 = 1, \quad q = 2\pi \lambda r_p Nu(T_1 - T_2)/C_p m_p, \quad m_p = \rho_p V_p,
\]

\[
a = (u - u_2)/\tau, \quad a_r = (v - v_2)/\tau, \quad 1/\tau = 3\mu Re C_d / \rho_p d^2, \quad d = 2r_p, \quad n = \int f dV.
\]
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\[ C_d = (1 + \exp(-0.43 / M_{12}^{4.67})) (0.38 + 24 / \text{Re} + 4 / \sqrt{\text{Re}}), \quad \text{Re} = \rho \|v - v_2\| d / \mu, \]
\[ c = \sqrt{\gamma p / \rho}, \quad Nu = 2 + 0.6 \sqrt{\text{Re} \text{Pr}^{0.33}}, \quad \text{Pr} = C_p \mu / \lambda, \quad M_{12} = \|v - v_2\| / c, \]
\[ F_z = -\int m \alpha_z f dV, \quad F_x = -\int m \alpha_x f dV, \quad \Phi = \int m ((u - u_z)\alpha_z + (v - v_z)\alpha_x - C_d) f dV \]

The numerical procedure for solving system and its verification were described at length elsewhere [3, 4]. The calculation parameters of gas in the system of equations (1) is made on an Eulerian grid, and used to calculate the particles Lagrangian coordinates.

**Results and Discussion**

Figures 1 and 2 illustrate the numerically computed two-phase jet flow seeded with 4-μm diameter aluminum particles.

Fig. 1 The computational domain (SW is the shock wave that envelops the compression layer) (a). The distributions of longitudinal gas flow velocity \( u \) (1), longitudinal particle velocity \( u_2 \) (2), and pressure \( p \) along the jet axis and near the obstacle (b, c).

Fig. 2 The distribution of pressure \( p \) on the axis (a), isobars and the pattern of flow streamlines near the obstacle (b). Impact velocities of aluminum particles \( u_{2w} \) (circles) calculated for various particle diameters \( d \) (c). Deltas in Fig. 2 c to show the impact velocities \( u_{2w} \) calculated for the case in which the nozzle size and distance to the wall increased 6 times.
From the pressure distributions in the vicinity of the wall (see Fig. 2) we can estimate the thickness of the compression layer: 
\[ \Delta = z_w - z_{sw} \approx 0.7 \text{Re} = 0.35 \text{mm} \]. The impact velocity of particles impinging onto the wall (Fig. 2) is 570 m/s, which value is sufficiently high for the particles to stick to the wall [5]. Figures 2a and b show the distribution of pressure and the calculated flow pattern in the region between the nozzle exit plane and the obstacle. In the compressed layer the jet flow turns so that to propagate, in a pulsational manner, in the normal direction along the obstacle. The pulsating compression layer give rise to acoustic waves distinctly visible in Fig. 2b. Fig. 2c with a circles show the results of calculations impact velocities onto the obstacle microparticles with different diameters, which are accelerated in the above nozzle. The highest impact velocity is achieved for 4 μm diameter particles. Smaller particles experience strong deceleration in the compression layer, whereas larger particles are accelerated insufficiently in the nozzle. Particles smaller than 1 μm in diameter are completely decelerated in the compression layer, so that, as they arrive at the wall, they possess zero impact velocity. Deltas in Fig. 2c to show the impact velocities \( u_{2w} \) calculated for the case in which the nozzle size and distance to the wall increased 6 times. The maximum impact velocity \( u_{2w} \) shifted to large sizes, and is due to particles 20 microns in diameter.

Conclusions

In the present study, a possibility is shown for microparticles impinging onto an obstacle to reach an impact velocity sufficient for sticking to the surface with the formation of a coating. The reduction of the microparticle diameter result to a corresponding reduction of the size of nozzles.

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REFERENCES