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Study of the gas-particle radial supersonic jet in the cold spraying

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ABSTRACT

For the first time numerical simulation of gas and particle flow produced by a radial supersonic nozzle under conditions of cold spraying on pipe inner surface is performed. The case of a jet discharging into ambient space and its interaction with pipe internal surface is considered. It is shown that, at a certain distance from the nozzle exit, the jet becomes unstable, and bending oscillations develop in it. The velocities and trajectories of particles accelerated in the radial nozzle and jet are evaluated. For this purpose "frozen" gas flow pattern was used. The calculated data for the gas flow and particle velocity are shown to be in good agreement with available experimental data. Verified numerical model is applied for calculation of gas and particle parameters under conditions of one of successful cold spraying tests. Obtained results are discussed. It is concluded that strong non-stationary bending oscillations of radial jet lead to particle deceleration, limiting maximal pipe inner diameter.

1. Introduction

Cold spraying is a fast developing method for coating production from powders. Perhaps none of the known methods for producing coatings has such versatility as cold spraying. Based on this method technologies are developed for coating production from powders of metals, ceramics, polymers and their mixtures on metal, ceramic and even plastic surfaces (more detailed review the reader can find in recently published works [1–4]). This diversity is achieved by development of new nozzle assemblies and proper selection of spray parameters. However, it is important that cold spray principle remains the same: it is necessary to impart to powder particles required velocity and temperature so that the coating begins to form itself.

Development of efficient technologies and equipment for coating production on internal cylindrical surfaces (pipes, etc.) is of practical interest. For this purpose, "classic" de Laval nozzle mounted on a long rod can be used [5–7]. With aid of this rod nozzle is introduced at a certain speed inside a rotating pipe, and a continuous coating is produced. Also annular supersonic nozzle is proposed in which gas and particle flow turns in supersonic part and coating is applied without rotation of the pipe, e.g. [8]. The use of radial supersonic nozzle [9,10] for coating production by cold spraying on the inner surface of cylindrical pipe, particularly of diameter <100 mm, allows doing this also excluding the operation of pipe rotation. In this case, the turn of two-phase flow occurs in subsonic part of the nozzle.

In this connection, systematic (both experimental and numerical) studies of the gas-dynamics of supersonic radial flows and the acceleration of particles in such nozzles is necessary. In reference [10] spraying experiments and some characteristics of spraying process and obtained coatings were described. Visualization data and profiles of Pitot pressure in supersonic radial jets emanating into ambient space at atmospheric pressure and impinging onto obstacles were reported in paper [11].

In publication [12], which was a continuation of [11], results obtained by treatment of experimental data were reported. From the radial distributions of Pitot pressure in jets emanating out of nozzles of various widths, the supersonic length of the jets was determined. The latter allows predicting the characteristic range of inner diameters of the pipes that can be coated from inside using one and the same spraying unit.

In this paper for gaining a better insight into the process of spraying coatings onto the inner surface of pipes with a supersonic radial nozzle, for the first time numerical modeling was performed. A comparison between calculated and experimental data obtained earlier on flow visualization and Pitot pressure measurements [11], as well as between calculated and measured particle velocities [10] are presented.

2. Numerical and experimental methods

2.1. Calculation procedure

Calculations were performed for experimental conditions in the computational domain shown in Fig. 1. Here, r_1 and r_2 are the inner and outer diameters of the inlet section, r_e is the radius of the outlet

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Nomenclature

d_{cr}	throat (critical) diameter of nozzle
d_{ex}	nozzle outlet diameter
$l_{ns} = r_w - r_e$	distance from the outlet radius of nozzle to the inner wall of pipe
M	Mach number
p_0	pressure in the nozzle pre-chamber (stagnation)
p	static pressure in gas flow
p_a	air pressure under normal conditions
p_{Pt}	Pitot-tube pressure
Re	Reynolds number
r	radius from nozzle axis
r_1	inner diameter of the inlet section
r_2	outer diameter of the inlet section
r_e	radius of the outlet section of nozzle
r_w	radius of the external boundary of the computational region
t	time
T_0	temperature in the nozzle pre-chamber (stagnation)
T_a	air temperature under normal conditions
T_j	period of oscillations
z	coordinate along nozzle axis
z_0	coordinate of vertical line that passes through the middle of the nozzle
z_1	coordinate of first wall of the nozzle
z_2	coordinate of second wall of the nozzle
$\delta_{ex} = z_2 - z_1$	nozzle channel width
$\lvert\nabla\rho\rvert$	gas density gradient

section of nozzle (the computations were carried out for two cases: $r_1 = 5$ mm, $r_2 = 9$ mm, $r_e = 36$; and $r_1 = 3$ mm, $r_2 = 5$ mm, $r_e = 20$ mm), and $\delta_{ex} = z_2 - z_1$ is the nozzle channel width (1 and 2 mm). The dashed lines show the boundaries of the external computational region BEFGD, with r_w being the radius of the external boundary of the computational region EF (in calculating the free jet, this radius was assumed equal to 70 and 40 mm respectively for nozzle radii 36 and 20 mm; in calculating the jet impinging onto an obstacle, the radius r_w was taken equal to the inner pipe diameter). For the distance from the outlet radius of nozzle to the inner wall of pipe, we introduce the designation l_{ns}: $l_{ns} = r_w - r_e$.

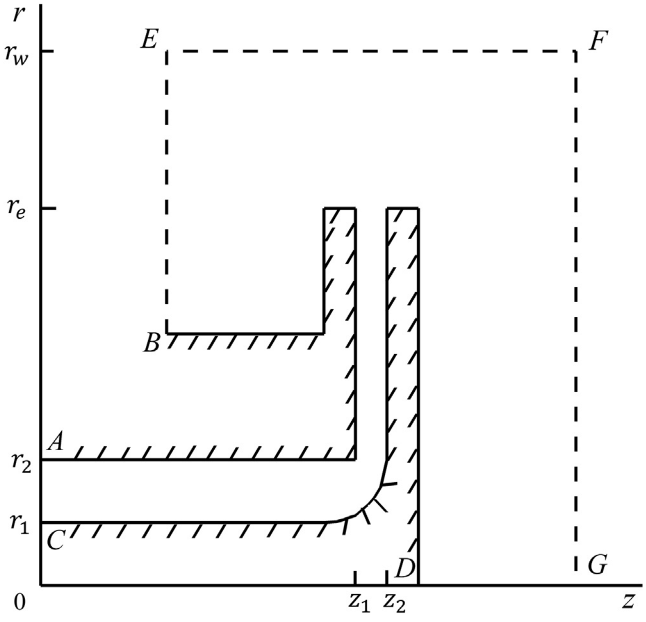

Fig. 1. The computational domain comprising a radial nozzle (shown with hatched solid lines) and the ambient space into which the gas flow emanates (a region bounded with dashed lines).

The computations were carried out for air at two values of pressure p_0, 1.5 and 2.5 MPa, and temperature T_0, 300 and 500 K, in the nozzle pre-chamber. The air flow was discharged into air under normal conditions, $p_a = 0.1$ MPa and $T_a = 300$ K. From the outlet of the radial nozzle, a supersonic overexpanded jet with Mach number M ≈ 3 and Reynolds number $Re \approx 2 \cdot 10^6$ was formed. The turbulent gas flow was governed by the equations of the *SST k–ω* model of turbulence [13]. The gas flow was calculated in axisymmetric approximation by an implicit scheme of second-order accuracy on a grid that involved $3.6 \cdot 10^5$ nodes. At the nozzle boundaries, the attachment condition was assumed, and at the outer boundaries *BE* and *FG*, soft boundary conditions were posed (that is, the derivatives of all flow quantities along the normal to the boundary were assumed to be zero). In the vicinity of nozzle walls, grid refinement was applied so that the condition $y^+ \approx 1$ was fulfilled [13]. Also, grid refinement inside the jet emanating into ambient space was performed. This method was used to study two cases, the case of the discharge of gas flow into ambient space and the case of the impingement of a jet onto an obstacle. In the first case, conditions of $p_a = 0.1$ MPa and $T_a = 300$ K were posed on the computational-region boundary EF. In the second case, the boundary EF was an obstacle with the adopted attachment condition. As the initial conditions for the gas, constant values of pressure p_0 and temperature T_0 were specified throughout the entire flow region; later those values decayed as the gas was discharged.

After a stationary flow was established in the nozzle, the calculated gas flow field was used to compute the velocities and trajectories of the particles that were supplied into the nozzle through the surface *AC*. In modeling the particle motion, a continuum-discrete model developed by the present authors in [14] was used. In that model, collisions of particles with the nozzle walls and with the obstacle were assumed elastic, and the influence of particles on the gas flow was ignored.

2.2. Experimental procedure

Experiments were of three different kinds and were made on three different experimental set-ups.

Measurement of pressure with a 0.8-mm diameter Pitot tube and visualization of the gas-flow field were performed in the test section of the T-326 wind tunnel at ITAM SB RAS. All measured parameters were registered using the automated data acquisition system of

T-326 wind tunnel. The system for optical visualization of flow was designed on the basis of an IAB-451 Schlieren instrument. The system permits taking Schlieren and direct shadow images with exposures ranging in duration from 4 μs to 1 s.

The supersonic jet under study was produced by a radial nozzle (see Fig. 2) with throat diameter $d_{cr} = 18$ mm. The nozzle outlet diameter was $d_{ex} = 72$ mm, and the Mach number, calculated by the one-dimensional ideal-gas model, M = 2.94. The experiments were performed at air pressure in the pre-chamber 2.5 MPa (the pre-chamber pressure was measured at point 8 in Fig. 2) and at room stagnation temperature. The width of the channel in the supersonic part of the nozzle, δ_{ex}, was chosen equal to 2 mm to increase resolution of Pitot pressure measurements and Schlieren visualization. Data obtained in wind tunnel were used for verification of calculation model on air flow pattern.

Particle velocities were measured with aid of home-made equipment using a shadow three-pulse method. Semi-conductor laser (WSTech UT5-40G-658, power 40 mW, wave length 658 nm, modulated by TTL-signal) illuminates particles by three short (20 ns) light pulses (after 200 and 600 ns from first), that are captured by camera (Videoscan-285/P-USB). In obtained photos, distances between particle