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Numerical study on the effect of the cold powder carrier gas on powder stream characteristics in cold spray

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ABSTRACT

The quality of coatings prepared by cold spray is largely determined by the primary parameters of the gas-powder stream. In this investigation, the parameters related to the power carrier gas, including the initial pressure differential between the main propulsion gas and the powder carrier gas, the diameter ratio of the nozzle throat to the powder injection tube and the particle injection location, are analyzed to examine their influence on the deposition characteristics. The results indicate that the particles in nozzle center region have relatively low impact velocity and temperature on substrates, which would bring about nonhomogeneity and nonuniformity of formed coatings. The larger the initial pressure differential, the smaller the diameter ratio and the longer the pre-chamber, the more intensive the heat and momentum exchange and mix between the two gas streams become. This intensive exchange and mix can compensate the effect of cold powder carrier gas to the impact velocity and temperature of the particles in the vicinity of nozzle center area. However, the overall impact parameters depend upon the mass flow rate percentage of each gas stream and the mixing degree of the two gas streams. Moreover, it is found that the particle dispersion has a certain relation with the turbulent kinetic energy generated on the interface of the two gas streams.

1. Introduction

Cold gas dynamic spraying (CGDS) is a relatively new coating technology developed in the past decades. During the process, microscale particles are accelerated by the supersonic gas stream through a converging-diverging nozzle as shown in Fig. 1 [1]. Only the particles with a velocity exceeding the critical impact velocity of sprayed materials can be deposited on the substrate [2]. Because the particle impact temperature is far below its melting temperature, CGDS can minimize effectively or eliminate unfavourable effects of oxidation, melting, evaporation and other common problems suffered in thermal spraying [3]. Therefore, the functional coatings fabricated by CGDS have been applied widely in various industrial fields, such as biomedical materials, metal near net shaping and aerospace [4–6].

In CGDS, the particle impact velocity and temperature play very important roles in the deposition efficiency and quality. Gilmore et al. reported that deposition efficiency is proportional to particle velocity [7]. Schmidt et al. demonstrated that coating microstructure and mechanical strength can be improved by raising the particle impact velocity and temperature [8]. Assadi et al. found that the particle critical impact velocity is decreased when increasing the impact temperature, and thus the particle flattening ratio, coating strength and deposition efficiency are enhanced [9]. In general, particle impact velocity and temperature are mainly dependent on the initial parameters of the propulsion gas. Nevertheless, they are also affected by other factors. Tabbara et al. compared different propulsion gases, and reported that helium has the best acceleration performance of particles [3]. Li et al. optimized the nozzle geometry to improve the acceleration of particles [10,11]. Park et al. also showed the effect of shockwaves, ambient pressure and the distance between substrate and nozzle exit [12]. Samareh et al. examined the effect of particle loading on the particle impact velocity [13].

In addition, some researchers have attempted to analyze the gas velocity profiles inside the nozzle and power stream characteristics. Alkhimov et al. showed that the gas flow inside the nozzle conforms to fully developed pipe flow and the “1/7” law in fluid mechanics [14]. Yin et al. also found the similar flow characteristics existed in rectangle and elliptical nozzles [15]. Gilmore et al. conducted an investigation on the in-flight particles at a distance of 25 mm from the nozzle exit, and concluded that most particles located the central regions gained a relatively higher velocity [7]. Wu et al. also examined the powder stream characteristics on substrates, and the results are consistent with that obtained by Gilmore [16]. Additionally, Lupoi et al. [17] and Suo et al. [18] examined in detail the effect of powder injector and nozzle dimension on particle distribution.

In CGDS, the gas stream consists of the main propulsion gas characterized by lower pressure and higher temperature and the powder

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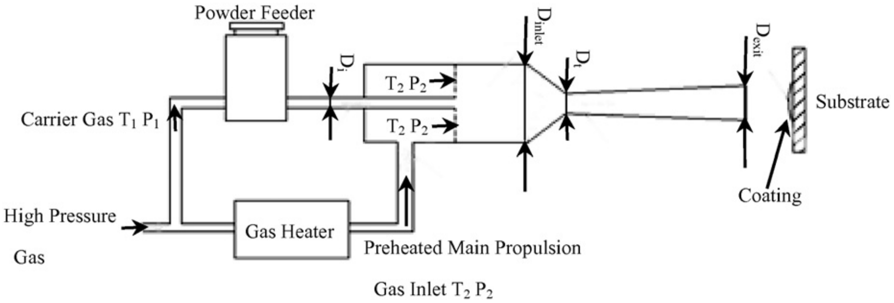

Fig. 1. Schematic of the cold spraying system.

carrier gas by higher pressure and lower temperature [19]. The influence of the main propulsion gas has been extensively studied. However, until recently, the effect of the powder carrier gas has been taken into account. The research results related to the powder carrier gas show that the carrier gas has a significant effect on the gas flow and particle acceleration. Tang et al. found the initial pressure differential between the two gas streams can change gas flow structure and bring some fluctuations on particle impact parameters [20]. Yin et al. reported the vital effect of the powder carrier gas on particle acceleration and deposition [21]. Additionally, Suo et al. found that particle impact velocity can be further increased when helium is chosen as the carrier gas [22].

Although some previous results have demonstrated that the effect of the carrier gas on single-particle targeted impact velocity [20] and multi-particle mean impact velocity are significant [22], the distributions of the particle impact velocity and temperature on substrates resulted from the mixing of the two gas streams are needed to be further investigated, which is extremely important to the homogeneity of the coatings formed by the deposition of powder streams. In fact, as the initial temperature and pressure differentials between the two gas streams exist ($T_1 < T_2$, $P_1 > P_2$, see Fig. 1), the gas acceleration process inside the nozzle is accompanied by a mixing process of the two gas streams. In accordance with the mixing degree, the gas acceleration performance, the exchange of momentum and heat between the gas streams and the particles, the particle trajectories and impact parameters are quite distinct from the published conclusions, for which the gas mixing situation is not taken into consideration. In this paper, the research focuses on further clarification of the effect of the cold powder carrier gas on gas flow through the nozzle and the distribution of impact velocity and temperature of the powder stream on substrate for the situations of fully and non-fully developed pipe flows. Furthermore, particle dispersion resulted from the powder carrier gas is also investigated. In this study, the parameters related to the powder carrier gas, such as initial pressure differential, diameter ratio and particle injection location are in detail examined by using the numerical simulation method.

2. Numerical methodologies

2.1. Computational domain and boundary conditions

In order to better guide the undergoing experiment on cold spraying, the parameters adopted in the simulation are set according to the present apparatuses in our laboratory. The structural parameters of powder injector and nozzles are given in Tables 1 and 2, respectively. Working parameters for different cases are listed in Table 3. A 2D axisymmetric model is established and presented in Fig. 2. In the figure, the boundary conditions are also illustrated, and the marks I, II, III and IV corresponding to four different powder injection locations are listed in Table 1. The computational domain is meshed by structured grids. Grid independent tests show 200,000–220,000 quadrilateral grids are sufficient for all the cases. In addition, the grids at the nozzle throat are refined.

2.2. Gas phase and particle phase

Fluent (version 6.3) is used to predict the steady gas flow as well as the particle dynamics. Compressed air is chosen as the main propulsion and power carrier gas. Moreover, the temperature-dependence of the viscosity is taken into account by the Sutherland law. To simulate the turbulence, the RNG k–ε model is adopted, in which the renormalization group theory makes the simulation more accurate and credible [23]. The corresponding governing equations can be found in Ref. [24]. As for the turbulence intensity and length scale, 1% and 20% of the nozzle diameter are set, respectively [25]. The high-order QUICK discretization scheme is applied. Furthermore, the grids adjacent to the wall are specially treated to make sure the non-equilibrium wall function can capture the near-wall flow characteristics at the lower *Re*. Namely, the first-layer grids on the boundary layer must be located where the parameter y + fall into the 30–60 range [26]. In the present study, y + meets this requirement. The nozzle wall keeps 300 K.

Copper particles are chosen as the sprayed feedstock. Since the particle volume fraction is less than 10% in the gas stream [15,20,22], particle movement is described by the discrete model, and the Lagrange equation of the force balance is expressed as

$$\frac{du_p}{dt} = F_D(u - u_p) + F \tag{1}$$

where u and u_p are the gas velocity and particle velocity, respectively, F is an additional acceleration force item, $F_D\,(u - u_p)$ is the drag force per unit particle mass, and the drag coefficient, F_D, is calculated by

$$F_D = \frac{18\mu}{\rho_P {D_P}^2}\frac{C_D Re}{24} \tag{2}$$

in which, ρ_p and D_p are the density and diameter of the particle, respectively, μ is the gas dynamic viscosity, Re is the relative Reynold number

Table 1
Parameters of the powder injector.

Particle injection location	I	II	III	IV
Location of the injection position	10 mm from nozzle inlet	Nozzle inlet	20 mm from pre-chamber inlet	40 mm from pre-chamber inlet
Diameter of the powder injector D_i (mm)			2	