The generation of high particle velocities by shock tunnel technology for coating application

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Summary. For enhancing coating quality, the shock tunnel technology is employed to achieve impact velocities of particles up to 1500 m/s for 10 μm solid particles. A calibration of the nozzle flow has been carried out by using a Pitot rake. The current conditions in the reservoir achieved so far are $p_0 = 140$ bar and $T_0 = 1800$ K. A high speed schlieren system is set up for flow visualization and also for velocity measurement of visible particles. For fine particles, both LDA and PIV methods are used for particle velocity measurements. The achieved results are in good agreement with a quasi-1D prediction.

1 Introduction

Thermal spray processes such as plasma spray, arc spray and high-velocity oxy-fuel spray are widely used for modern coating applications. In these techniques, the coating material suffers very high temperatures, which results in melting and chemical reactions of the coating material. This problem is generally avoided in the cold gas-dynamic spray (CGS) technique [1]. The conventional CGS process basically uses the energy stored in high pressure compressed gas to accelerate fine powder particles to very high velocities in a range between 500 - 1000 m/s [2]. According to the prevailing theory for cold-spray bonding [3], the particle velocity should exceed a minimum (material-dependent) critical velocity to achieve deposition and, therefore, it is desirable to further increase the impacting velocity of particles in order to enhance the quality of CGS and to extend the application range of CGS. A modified cold gas-dynamic spray technique is proposed to increase the solid particle velocity up to 1500 m/s [4]. This method uses the super/hypersonic shock tunnel technology to generate a reservoir condition with high temperature and high pressure. The particles are injected into the nozzle flow downstream of the nozzle throat after the nozzle flow is fully established.

A theoretical model based on gas-particle flows is also presented in [4] to describe the behavior of the flow and the diluted solid particles during the modified cold-spray process. This quasi-1D model is capable to consider non-equilibrium effects of the gas phase due to high reservoir temperatures, and the influence of wall friction and heat transfer. Based on the parametric study [4], a nozzle with optimized theoretical performance has been chosen resulting in a conical nozzle with a half opening angle of 2.8° and a length of 32 cm. The throat diameter amounts to 7.8 mm, and the exit diameter is given by 39.7 mm. The particle injection device is fixed in the LPS (Low Pressure Section) of the shock tube and extends into the supersonic nozzle part. For this, a small tube (outer diameter 3.0 mm, inner diameter 1.2 mm) reaches into the divergent nozzle part so that the injection position is about 52 mm downstream of the throat.

2 Experimental setup and methods

2.1 Shock tunnel and Pitot rake

The shock tube has an outer diameter of 108 mm and an inner diameter of 56 mm. This tube is made by stainless steel and is able to sustain very high pressures up to 1000 bar. A schematic drawing of the setup is shown in Fig. 1. The shock tube has a high pressure section of 2.0 m and a low pressure section of 4.5 m length.

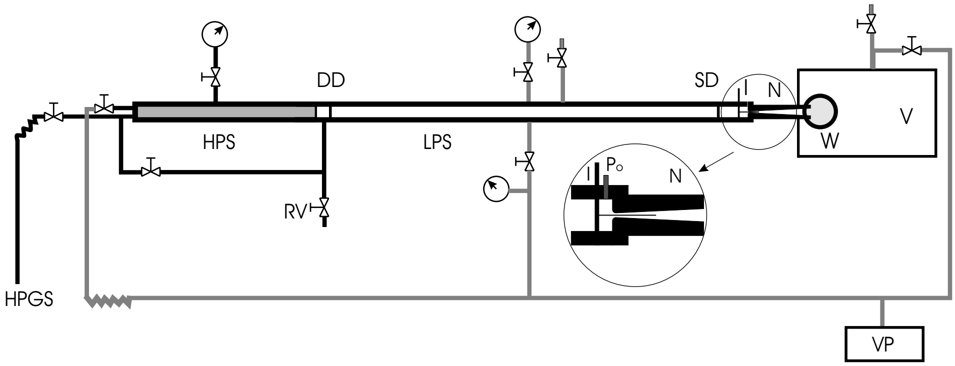


Fig. 1. Schematic drawing of the shock tunnel with peripheries. HPGS, high pressure gas supply; HPS, high pressure section; DD, double diaphragm chamber; LPS, low pressure section; I, injection device; N, nozzle; W, test window; V, vacuum tank; VP, vacuum pump, SD: second diaphragm.

In order to determine the free stream flow conditions downstream of the nozzle exit, a Pitot rake is used, which consists of five Pitot tubes connected with five Kulite pressure transducers, and a sphere installed with a coaxial thermocouple at its stagnation point. The reservoir pressure is directly measured by a Kistler pressure transducer mounted shortly upstream of the nozzle entrance. The reservoir temperature and free stream conditions are derived from the heat flux deduced from the thermocouple signal, the Pitot pressure and the static pressure employing the method described in [5, 6].

2.2 Particle velocity measurement: high speed photo system, LDA and PIV

A schlieren system is set up for flow visualization, which allows to take 16 schlieren photos in one experiment with a time interval between two successive photos of down to 1 μs, which is also very useful for the determination of the velocity of visible particles.

For velocity measurements of fine particles, a laser Doppler anemometer (LDA) system and a particle imaging velocimetry (PIV) system have been set up. In order to measure very high particle velocities, a very small angle is used in the LDA system, which results in a measurement volume of $17 \times 0.16 \times 0.16$ mm^3. For the PIV measurements, a holographic double-pulse laser system (JK Laser system 2000) with a pulse separation time in the microsecond range is adopted to create a laser light sheet (thickness 0.5 mm) perpendicular to the nozzle axis. A Kodak megaplus ES1 CCD camera is employed to acquire either two images in two frames or one double exposure image in a single frame within a pulse delay in the microsecond range. The image data is then analyzed with the PIV software to obtain the particle velocity field.

3 Results and discussions

3.1 Flow calibration

Measured temperature and pressure histories in the reservoir are shown in Fig. 2. Initially, the HPS is filled with a mixture of helium (partial pressure 140 bar) and air (partial pressure 170 bar), and the LPS is at atmospheric pressure. A pre-cutted copper diaphragm of 0.5 mm thickness is mounted in the nozzle, and the dump tank is evacuated to a low pressure of about 180 Pa. The well validated shock tube simulation code KASIMIR [7] has been utilized for the comparison of the experimental results with the theoretical prediction, shown as dotted lines. An extension of the KASIMIR software package has been done to simulate the case that the driver gas is a mixture of helium and air. It should be mentioned that equilibrium effects are taken into account in KASIMIR. The reservoir temperature in the experiment slightly decreases with time and the testing time is about 2 ms for $T_0 \approx 1700$ K and 5 ms for $T_0 \approx 1500$ K.

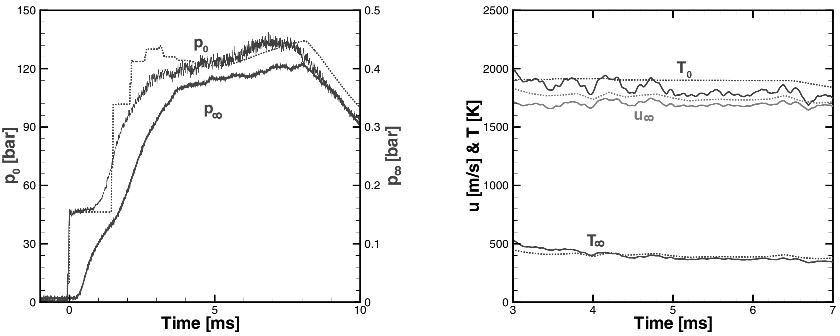
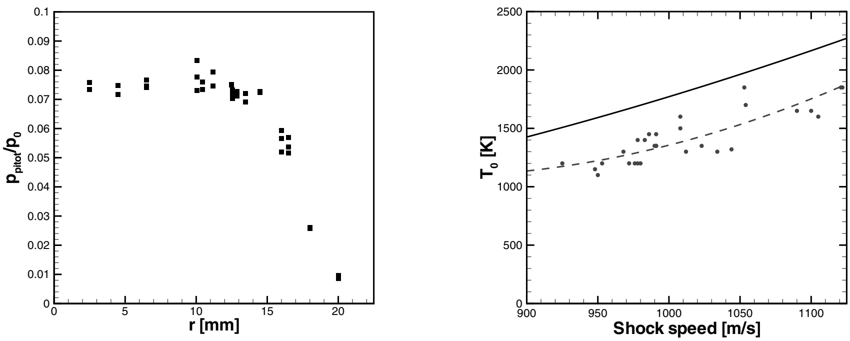


Fig. 2. Experimental results (solid lines) and corresponding numerical results (dotted lines). Reservoir pressure p_0 and static pressure histories p_∞ (left); deduced reservoir temperature T_0, free stream velocity u_∞ and temperature T_∞ (right). Initial condition: $p_4 = 310$ bar (partial pressure of helium 140 bar, partial pressure of air 170 bar), $p_1 = 1$ bar.

By changing the transverse position of the Pitot rake from shot to shot, the Pitot pressure profile along the radius of the nozzle exit has been obtained, see Fig. 3(a). The Pitot pressure is scaled by the actual reservoir pressure because the reservoir pressure slightly varies for every experiment. Each point in this figure represents an average value over the testing time. This Pitot pressure profile clearly indicates that the core flow region of the jet ($0 < r < 12$ mm) is repeatable from shot to shot. Figure 3(b) provides an experimental as well as theoretical relation of the reservoir temperature with the shock speed by KASIMIR. The relatively large scattering of the experimental data in



(a) (b)

Fig. 3. **(a)**: Pitot pressure profile along the radius at the nozzle exit. **(b)**: Relation of the reservoir temperature with the shock speed. Solid line: theoretical prediction by KASIMIR; dashed line: polynomial fit of experimental data.

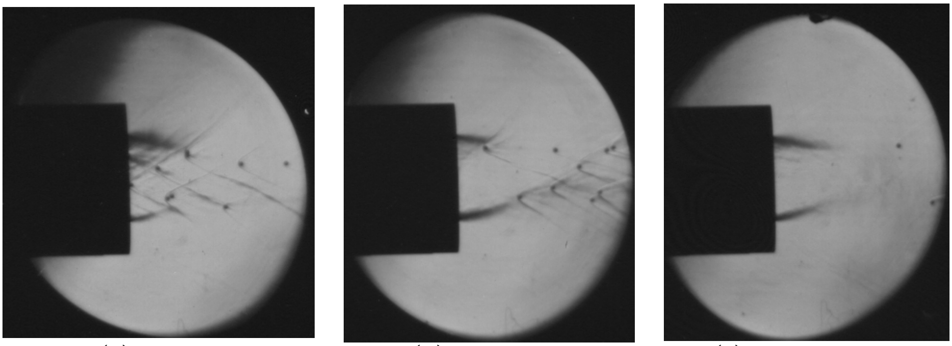
Fig. 3(b) is because the partial pressure of helium is not the same for all experiments. Furthermore, the filling process of the different gases is not yet optimized and therefore, might cause variations for each experiment. The general deviation between the theoretical and experimental values in Fig. 3(b) is caused by the mixing process taking place at the contact surface in the experiments.

3.2 Particle velocity measurements

For first experiments, some big glass spheres (diameter 2 mm) were put on a flat surface of the injection device. The particles can be identified in the schlieren photos as shown in Fig. 4. In this case, the particle velocity deduced from the schlieren photos is about 200 m/s. Then smaller glass particles with 0.6 mm diameter are used. The measured mean particle velocity is about 350 m/s, which is almost the same as given by the theoretical prediction (356.6 m/s) utilizing the quasi-1D code, which has also been used for the parametric study. For this experiment the reservoir condition is given by $p_0 = 120$ bar and $T_0 = 1800$ K.

For 15 μm stainless steel particles added on a flat surface of the injection device, the arriving time of particles is first measured by the LDA system with time division of 1 ms, see Fig. 5. It can be found that the particles arrive at the nozzle exit after a delay of 900 μs and the particle flow lasts for several milliseconds. Then a smaller time division (50 μs) is used for the particle velocity measurements. The mean particle velocity measured by the LDA method is about 1050 m/s for the reservoir condition of $p_0 = 140$ bar and $T_0 = 1800$ K.

Up to now, experiments with PIV are still running for different conditions. In this paper, only preliminary results of the PIV measurements are presented for air as driver gas. Fig. 6 shows double-exposure images for the single frame mode for stainless steel particles of mean diameter of 15 μm added in the reservoir (left) and in the injection tube (right). By using the particle-pairing method, it is found that the averaged particle velocity is about 1220 m/s in the left image and 890 m/s in the right image. The cross-



(a) t = 3.30 ms (b) t = 3.45 ms (c) t = 3.60 ms

Fig. 4. Schlieren pictures for 2 mm glass particles added in the nozzle prior to the experiment.

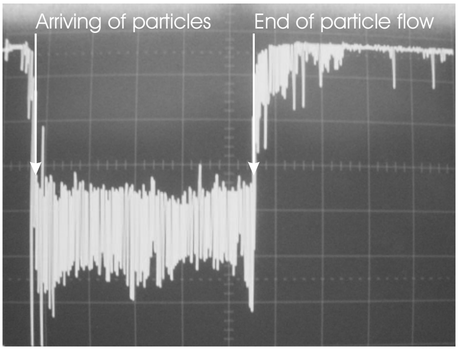


Fig. 5. Determination of the arriving time of particles by the LDA system, time division 1 ms.

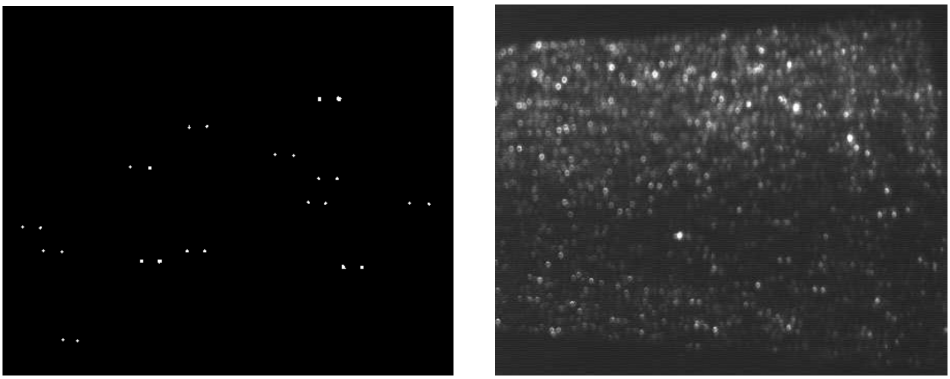


Fig. 6. Double-exposure images in single frame mode for particles added in the reservoir (left, interval 2.2 μs) and in the injection tube (right, interval 1.48 μs). Initial condition: $p_4 = 200$ bar, $p_1 = 1$ bar.

correlation method can also be used to deduce the velocity field by capturing two images in the double frame mode. The mean particle velocity deduced by the cross-correlation method is about 897 m/s, which is the same as for the particle-pairing method.

4 Conclusion

The shock tunnel technology is employed to achieve particle velocities of more than 1000 m/s for 10 μm solid particles. A calibration of the nozzle flow has been carried out by using a Pitot rake and a sphere for measuring the stagnation point heat fluxes. The current conditions in the reservoir achieved so far are $p_0 = 140$ bar and $T_0 = 1800$ K. A high speed schlieren system is set up for flow visualization and also for velocity measurements of visible particles. For fine particles, both LDA and PIV methods are used for particle velocity measurements. Results are in good agreement with the theoretical prediction by the quasi-1D method.

For today's existing technologies, like e.g. plasma coating, the reservoir temperature amounts to 7000-20000 K and the pressure to 1 bar, resulting in a typical particle velocity of about 200-300 m/s. High particle velocities are achieved with the cold gas coating technique, where the reservoir temperature is about 1000 K, the reservoir pressure about 50-100 bar and the typical particle velocity in the order of 600-1000 m/s. This shows that the conditions achieved in this work so far (p_0=140 bar, $T_0 = 1800$ K, expected copper particle velocity for $d = 10\mu$m about 1329 m/s) are already beyond existing technologies. For higher particle velocities, it is still necessary to increase the reservoir condition, for instance to $T_0 \approx 2100$ K and $p_0 \approx 200$ bar, which can be realized by increasing the partial pressure of helium or using pure helium. More PIV experiments will be carried out in the near future for higher reservoir conditions, and different particles in size and material. A substrate will also be mounted near the nozzle exit to study the coating process and to evaluate the quality of the coating layer.

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