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AN INVESTIGATION ON POWDER STREAM IN COLD GAS SPRAY (CGS) NOZZLES

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Abstract. *The exponential increase of industrial demand in the past two decades has led scientists to the development of alternative technologies for the fast manufacturing of engineering components, aside from standard and time consuming techniques such as casting or forging.*

Cold Gas Spray (CGS) is a newly developed manufacturing technique, based upon the deposition of metal powder on a substrate due to high energy impacts. In this process, the powder is accelerated up to supersonic speeds in a converging-diverging nozzle, typically employing air, nitrogen or helium as carrier gas. Recent developments have demonstrated significant process capabilities, from the building of mould-free 3D shapes made of various metals, to low porosity and corrosion resistant coatings of titanium.

In the CGS process, the particle stream characteristics during the acceleration process become important in relation with the final geometry of the coating. Experimental studies have shown the tendency of particles to spread over the nozzle acceleration channel, resulting in a highly dispersed stream.

This paper presents an investigation on the powder stream characteristics in CGS supersonic nozzles. The powder injection location was varied within the carrier gas flow, along with the geometry of the powder injector, in order to identify their relation with particles trajectories. Computational Fluid Dynamic (CFD) results are presented, along with experimental observations.

1 INTRODUCTION

The development of manufacturing processes is most definitely one of the most active research field, which has increasingly attracted the interest of scientists and institutions. Relatively simple techniques such as casting or forging have been widely implemented since the industrial revolution, and nowadays still play an important role in the world-wide manufacturing industry.

However, the increasing demand of high quality products and friendly industrial environments is driving the attention away from ordinary means of manufacturing, to focus research efforts on the development of alternative technologies. During the last two decades, new methods have been introduced, with the potential of providing a step change to standard industrial processes. One example is Rapid Prototyping (RP) [1], a method capable of the automatic construction of 3D physical objects using additive manufacturing technology. In this process the shape of the final product is simply modelled with a 3D-CAD software system, and then automatically built layer by layer throughout the employment of various techniques such as Fused Deposition Modelling (FDM), Stereolithography (SL) or 3D-printing (3DP). Laser material processing [2] is another example of a manufacturing technology recently developed, and based upon the employment of a wide range of lasers to perform conventional operations such as marking, cutting, drilling and welding. The advantages of using lasers for manufacturing operations can be various, from a total reduction of tool forces to a much higher level of process efficiency and final product quality. Another method, recently patented by Alkhimov [3] and known as Cold Gas Spray (CGS), has widely attracted the interest of industry. In this process [4], material (typically metal) in a powder form is injected within a supersonic gas stream (carrier gas). Particles travelling at such high speed are shown to deposit upon impact with a substrate material, and form a coating. Carrier gases are typically helium or nitrogen, accelerated up to supersonic velocities through converging-diverging nozzles. Helium is a relatively expensive gas, but it is capable of generating velocity magnitudes in the order of thousands meters per second, due to its high sonic speed. Pattison at al [5] have explored the potential of Cold Spray to fabricate mould-free 3D geometries, and successfully produced prototype components made out of titanium, aluminium and copper, with helium as carrier gas. Optimum particle velocity requirements to form a deposit have been extensively studied, against their size and material [6,7]. On the other hand, Bray at al [8] have further improved the process with the integration of a laser apparatus in the system. In this case, a laser beam is fired on the substrate surface during the spraying process, in order to provide extra energy in the form of heat to the impingement zone, in such a way to facilitate bonding. It was also demonstrated that the implementation of the laser system would provide a dramatic decrease in particles deposition velocity, therefore the achievement of relatively strong materials deposits (such as titanium) with nitrogen as carrier gas was demonstrated to be possible.

In Cold Gas Spray (CGS), the geometry of the powder beam flowing out the nozzle becomes important in relation to the final contour and achievable size range of the deposited coating. This paper presents results from a Computational Fluid Dynamic (CFD) investigation on powder stream characteristics against different supersonic nozzles types and powder injection locations. The Lagrangian Discrete-Phase-Modelling (DPM) algorithm implemented in the Fluent Inc. code was used in this study. Numerical results by the CFD analysis are also compared against experimental observations.

2 COLD SPRAY SYSTEM

A schematic diagram of the in-house Cold Gas Spray system working principles developed at the University of Cambridge in shown in Figure 1. The spraying gun of the system comprises of a supersonic converging-diverging nozzle and a powder injector. Under operating conditions, a pressurized carrier gas is fed through a number of ports, to enter the nozzle inlet section of length *a*. At the same time, a mixture of gas and powder is delivered form a powder feeder to the powder injector shown in the figure. The amount of gas used in such mixture is only a small fraction of the carrier gas flow rate (approximately 10%). The carrier gas will therefore expand up to atmospheric pressure and accelerate throughout the supersonic nozzle total length (*a*+*b*), giving sonic velocity at correspondence of the throat and supersonic speed at the exit. Particles (typically metals) are dragged by the carrier gas up to high velocity magnitudes, resulting in severe plastic deformation processes upon impact with a solid substrate positioned at a distance SoD (Standoff Distance). As a consequence, bonding with the substrate occurs and a coating process can be initiated. Typically, the substrate is connected to a CNC table to allow for movement along the X and Y direction at an imposed Transverse Speed (TS), in such a way to control and shape the coating accordingly.

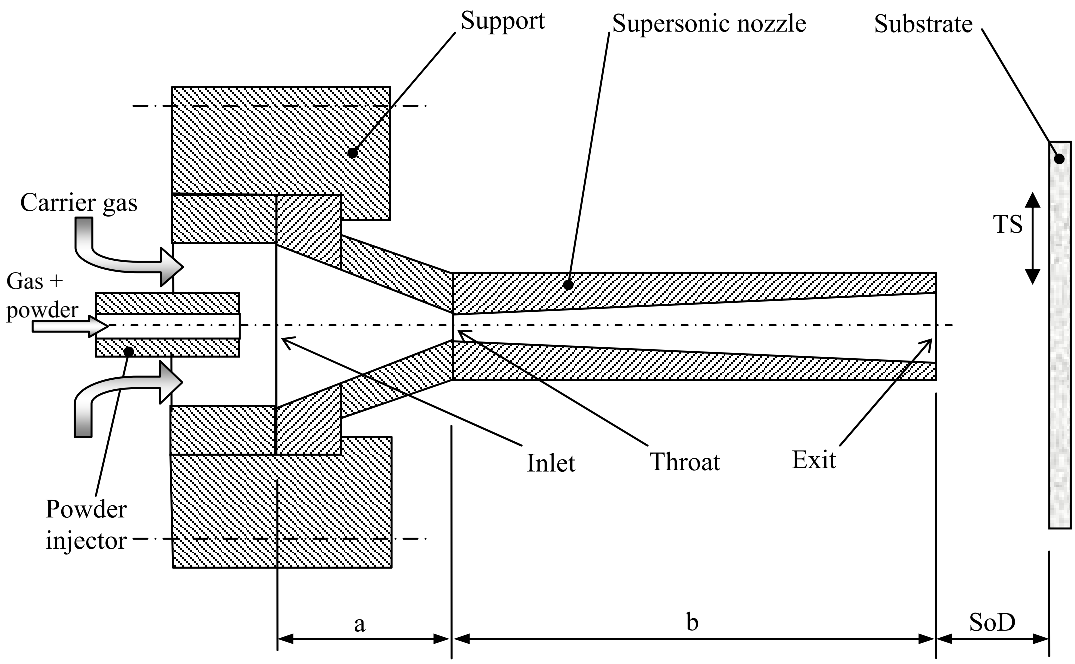

Figure 1: Cold Gas Spray (CGS) system working principles.

The carrier gas used in this system is nitrogen, delivered with a maximum static pressure of 30bar from a Multiple Cylinders Pallet (MCP) source. The level of pressure at the nozzle can be adjusted through a computer controlled regulator. On the other hand, a high-pressure powder feeder (Praxair, 1264HP) is implemented to deliver particles into the nozzle inlet. Typical particle sizes optimal for Cold Spray applications can vary between 10μm and 60μm diameter. The supersonic nozzle internal profile of the diverging section of length *b* is critical with respect to the system performance. A De-Laval geometry (simple conical) is usually preferred to more complex shapes for easiness of manufacture. A typical design is characterized by a circular cross-section nozzle (axial-symmetric) with a 2mm-6mm throat-exit diameter respectively, and a variable length *b* tailored for a specific application. In longer nozzles particles are entrained in the jet stream for longer periods, therefore the impact velocity is higher. In the current system, the maximum achievable carrier gas velocity is in the order of 650m/s with a De-Laval nozzle (*b*=180mm), giving a particle impact speed in the range between 450m/s and 550m/s, depending on feedstock powder type of material and size. Smaller particles and light-weight materials would travel faster in comparison to larger geometries and heavier metals. Supersonic nozzles are typically manufactured in tool steel and polished until the achievement of a surface finish of approximately 0.5Ra across the internal profile. They can also be heat-treated in order to reach the required level of hardness, in order to avoid erosion due to particles abrasion with the nozzle channel surface.

3 CFD SIMULATION OF A COLD SPRAY NOZZLE

The design of the supersonic nozzle acceleration channel is certainly most critical in the Cold Spray process. It dictates the exit carrier gas velocity, i.e. particles speed, for given inlet conditions. Also, nozzles are costly components to manufacture as tight tolerances are required in supersonic regimes. With this respect, it is fundamental to accurately predict their performance based on theoretical calculations. The Quasi-One-Dimensional flow theory or the Method of Characteristics [9,10] provide insights into the basic principles of nozzles contours for compressible flows. However, with the development of advanced numerical techniques such as Computational Fluid Dynamic (CFD), the study of other relevant parameters such turbulence generation-dissipation within the jet flow and the addition of multi-phase capabilities is nowadays achievable.

Fluent Inc. (version 6.3.26) software was used in this work to predict the performance of various Cold Spray nozzles with circular cross-section, combined with a study of particles trajectories and velocity within the jet flow. The volume fraction of particles within the carrier gas in Cold Spray flow is small (<10%), therefore particle-particle and particle-carrier gas interactions are assumed to be negligible. As a consequence, a Lagrangian solution given by the Discrete-Phase-Model (DPM) [11] algorithm implemented in the code was used to provide information on powder beam characteristics. The "high-mach-number" drag low was applied in the simulations. In order to take into account for particle dispersion due to turbulence, the "stochastic-tracking" model was used with 35 as number of tries.

A steady-state solution of carrier gas flow (nitrogen) was obtained with the density-based solver, which better adapt to supersonic regimes in comparison to the pressure-based. The ideal-gas low was selected from the material properties list, in order to take into account compressibility effects. In addition, the k-ε-realizable turbulence model was employed in this case. Flows were solved in 2D through the double precision method (2ddp), however in order to take into account for three-dimensional effects on

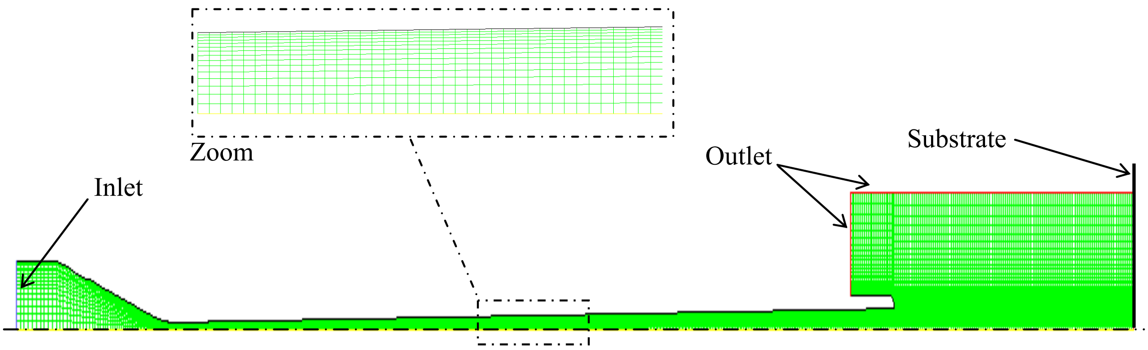

Figure 2: Modelling and meshing of a supersonic nozzle

the gas expansion process, the "axial-symmetric" option was enabled. In all cases, convergence was achieved up to the second-order scheme.

The geometry was meshed with quadrilateral elements over the entire domain. In order to achieve a grid-independent solution, a variable number of cells between 50000 and 120000 was required, depending on the nozzle type and overall size. The nozzle inlet and outlet surfaces were set as pressure-inlet (giving the value of the actual operating pressure with a maximum of 30bar) and pressure-outlet (1bar absolute) boundary conditions, with the attention of positioning the outlet far enough from the actual nozzle exit, as in the example shown in Figure 2. The substrate was modelled as a rigid wall at the distance SoD from the nozzle exit location.

4 PARTICLES STREAM ANALYSIS

The development of a Computational Fluid Dynamics (CFD) solution for Cold Spray nozzles is of particular interest for the analysis of the particle stream. In fact, the achievable shape of the coating is strongly dependent on its geometrical characteristics. With this respect, different nozzles and powder injector configurations have been experimentally tested, and their behaviour predicted by numerical simulations for a comparative analysis.

4.1 Spraying configurations

Figure 3 shows the spraying nozzles and injectors used for the experiments presented in this paper. Three configurations were tested, (1), (2) and (3). Geometrical and operating parameters are summarized in Table 1. In configuration (1) and (2), the powder is injected in the inlet section of the nozzle, therefore before the throat, through a 2mm internal diameter powder injector. Configuration (2) is similar to (1), therefore particles are injected in the nozzle inlet volume section, however the nozzle in this case is characterized by a shorter diverging length and wider exit cross-section. On the other hand, in configuration (3) the powder injector is longer than in (1) and (2) and mounted through the throat to allow powder injection in the low-pressure supersonic region of the nozzle. The injector exit is placed at a distance of 50mm from the throat. In all cases, the injector inlet diameter is 6mm; however the exit diameter varies case by case.

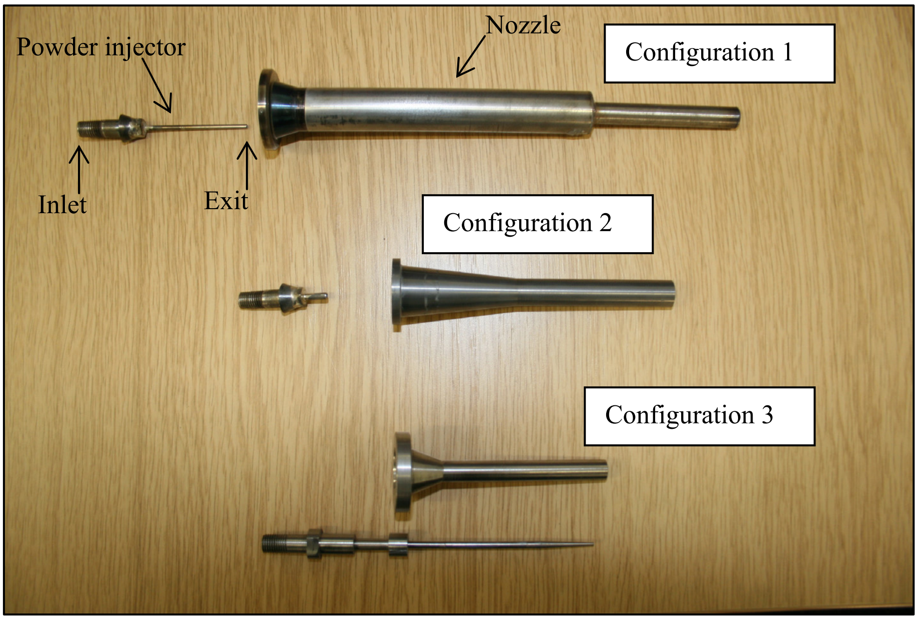

Figure 3: Spaying nozzles and powder injector configurations

CONFIGURATION	1	2	3
Throat diameter	2mm	2.7mm	4mm
Inlet diameter	22mm	18mm	20mm
Exit diameter	6mm	8.1mm	4.6mm
Inlet lenght (*a*)	30mm	50mm	17mm
Supersonic lenght (*b*)	180mm	65mm	70mm
Inlet static pressure	30bar	30bar	30bar
Outlet static pressure	1bar	1bar	1bar
Injector exit diameter	2mm	2mm	0.9mm

Table 1: Configurations parameters

4.2 Numerical and experimental results

Figure 4 shows contour plots results of velocity magnitude for the configuration1 nozzle system, at correspondence of the inlet and outlet regions. The actual pressure-inlet boundary surface was made wider than the real inlet section from Figure1, in order to simulate static conditions and facilitate numerical convergence. The gas maximum velocity is 674m/s, giving a supersonic flow about 3.5 times faster than the speed of sound. The nozzle is shown to be over-expanded, therefore oblique shock waves

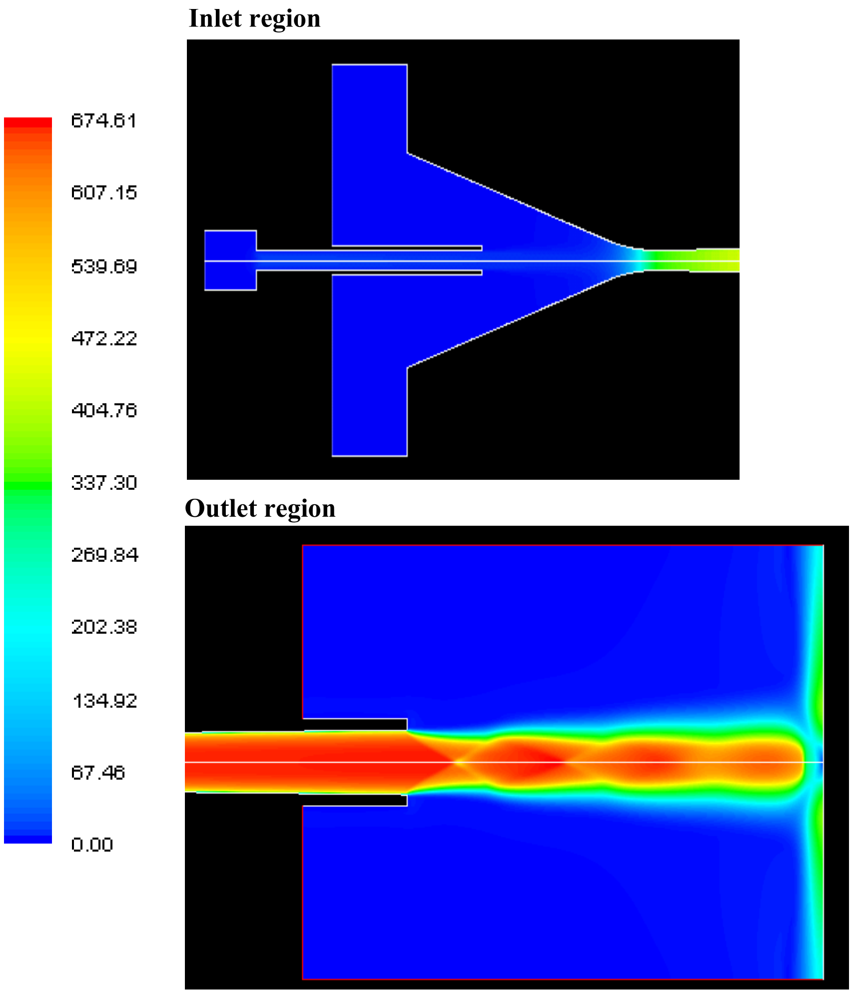

Figure 4: Velocity magnitude contours (m/s) at inlet and outlet - configuration1

develop at the exit. The Standoff Distance (SoD) between nozzle exit and substrate was set to 40mm.

When particles are released through the injection port, their trajectories does not stay close to the nozzle centreline, but diverge to occupy approximately the entire volume of the acceleration channel in the outlet region, as shown in Figure 5. Such effect is partially caused by the particles rebound against the powder injector wall where the cross-section reduces; therefore particles exit the injector with an angled velocity vector.

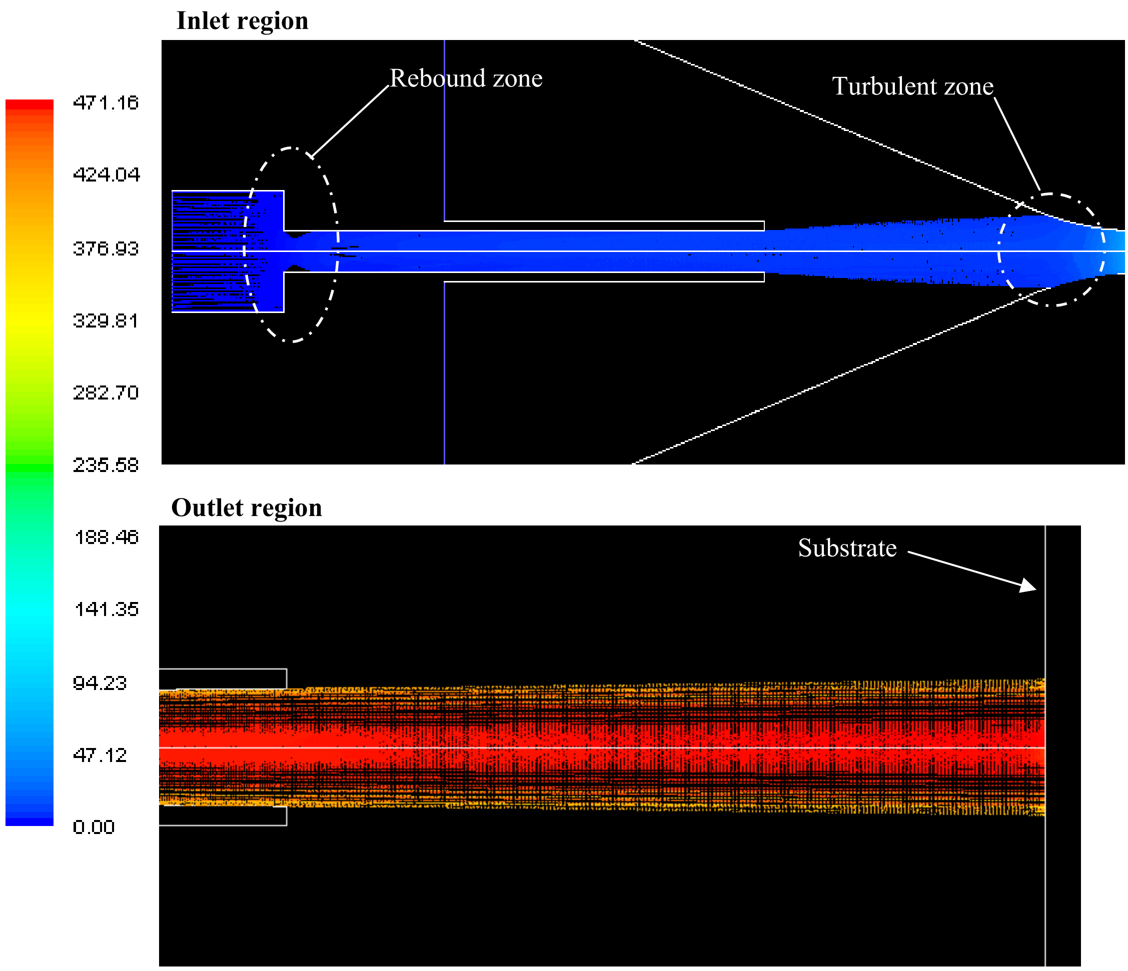

Figure 5: Particles beam (20μm copper) coloured by velocity magnitude (m/s) - configuration1

In addition, turbulence generated within the nozzle flow plays an important role. With this respect, Figure 6 shows the computed turbulence kinetic energy against the nozzle centreline. Simulations results have shown that the turbulent activity increases as the gas accelerate in the inlet region of the nozzle and raises its Reynolds number. A peak is observed nearby the throat. However, when the flow becomes supersonic the dilatation-dissipation effect [12] is predominant and the turbulent activity diminishes. When particles cross the throat, they are still relatively low in speed and momentum; therefore their trajectory is most likely to be affected by the turbulence activity generated in this region.

Figure 7 (a) shows the computed particles distribution (20μm spherical copper) over the substrate surface area. Particles are observed to mostly concentrate over a zone of approximately 3.5mm radius, therefore their footprint extend up to a region of 7mm diameter. Figure 7(b) shows a close-up picture of an experimental coating of copper on

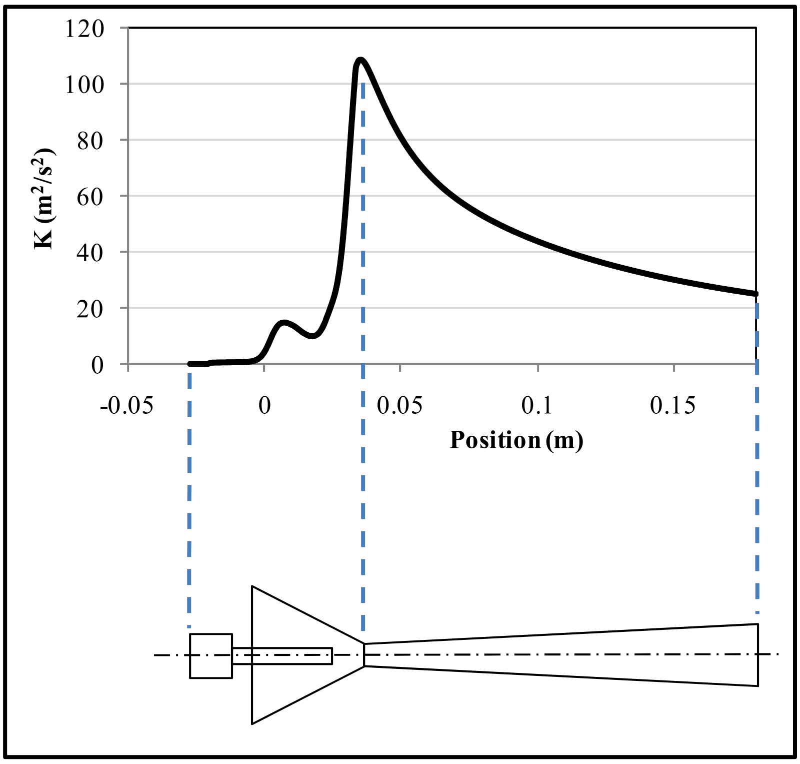

Figure 6: Specific turbulence kinetic energy (K) against nozzle centreline - configuration1

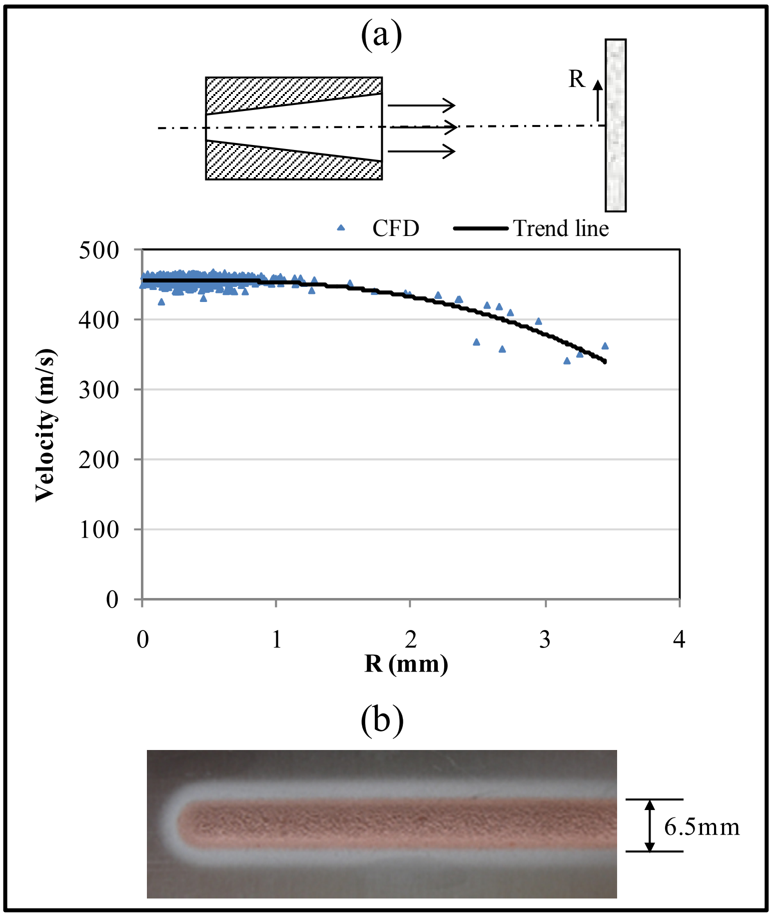

Figure 7: (a) Particle beam distribution (20µm copper) against impact velocity over the substrate surface - configuration1. (b) Experimental copper track on aluminium for configuration1

an aluminium substrate. The track was obtained from copper powder (Sandvik Osprey Ltd. - HC Cu -32+10μm spherical), at the Transverse Speed of 400mm/min. The measurement of the track width (6.5mm) compares well with the predicted powder beam distribution on the substrate from the numerical analysis. The powder size chosen for the CFD model corresponds to the average size of the commercial range. A 3D model of this configuration was also developed; similar results were observed in comparison with the 2D axial-symmetric case.

In similar ways, a model of the configuration2 system was solved. The nozzle has shown comparable characteristics to the configuration1 setup, and the computed copper powder beam geometry in the outlet region is shown in Figure 8, coloured with particles velocity magnitudes. Figure 9(a) shows the powder distribution across the substrate surface for this configuration. The beam seems to be more uniformly distributed in comparison with the previous case, however a larger footprint of over 10mm diameter is predicted. The nozzle was experimentally tested, and a track width of 8mm was

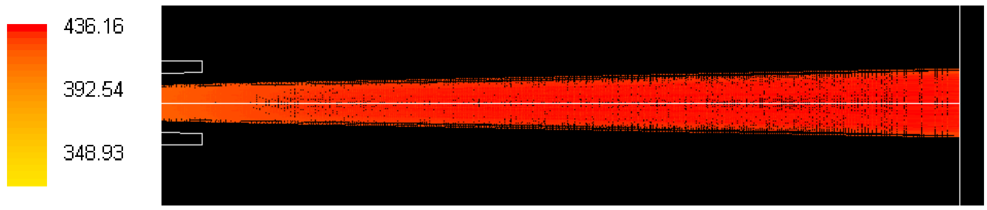

Figure 8: Particles beam (20μm copper) coloured by velocity magnitude (m/s) – configuration2

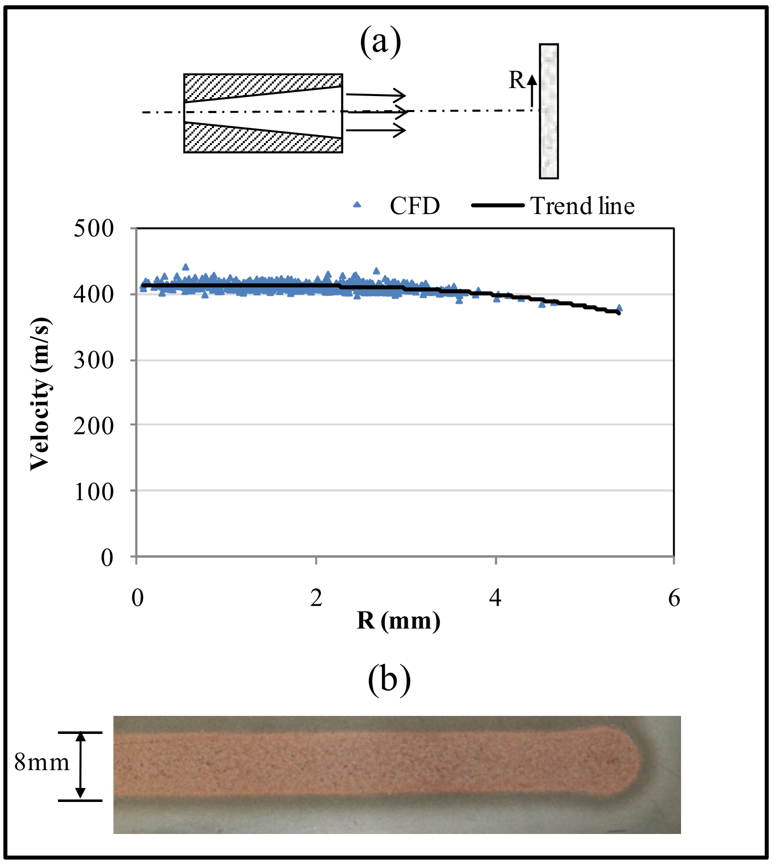

Figure 9: (a) Particle beam distribution (20μm copper) against impact velocity over the substrate surface – configuration2. (b) Experimental copper track on aluminium for configuration2

measured. Also in this case experimental observations are comparable with numerical results. Due to the relatively short acceleration channel *b* of the configuation2 nozzle, the deposition velocity of copper could only be achieved with longer SoD, so that to increase the residence time of particles within the jet flow, i.e. their impact speed. For this reason the Sod was set to 100mm, in both the experimental and numerical analysis.

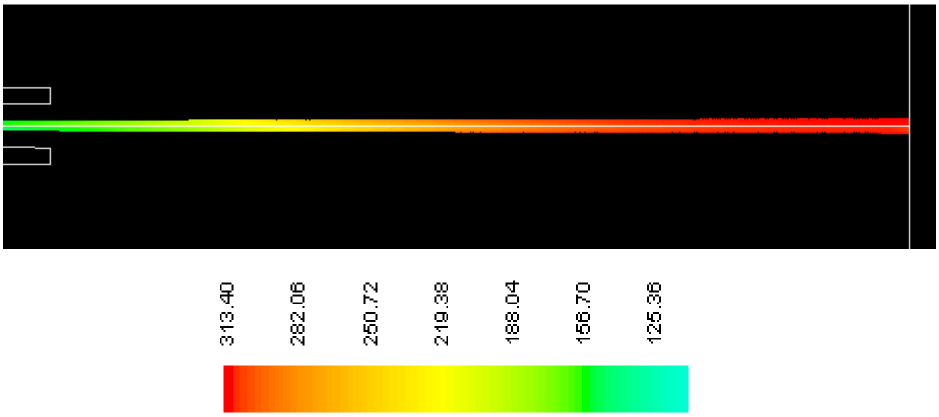

Figure 10: Particles beam (20µm tin) coloured by velocity magnitude (m/s) – configuration3

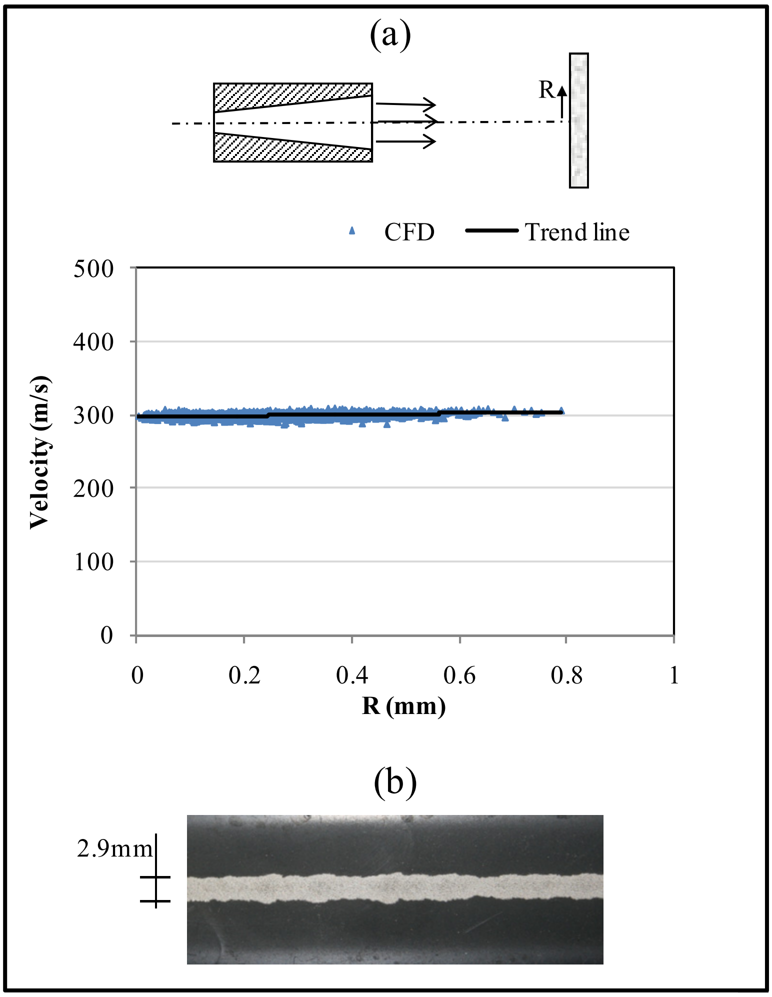

Figure 11: (a) Particle beam distribution (20µm tin) against impact velocity over the substrate surface – configuration3. (b) Experimental tin track on PC/ABS for configuration3

Figure 10 shows computational results of the third spraying system setup (configuration3). In this case, powder is injected axially and within the low pressure supersonic region of the nozzle, therefore after the throat at a distance of 50mm from it. Tin powder (spherical 20µm particles diameter) was simulated for this configuration. As powder is injected after the turbulent zone shown in Figure 5, a narrower beam is expected to be generated. Results plotted in Figure 10 and 11(a) confirm such prediction, giving a beam diameter of 1.6mm for a 20µm particles jet; therefore 2.8 times smaller than the nozzle exit diameter. The SoD was set to 100mm. Also, as shown in Figure 11(a), the particles velocity distribution over the track radius *R* is more uniform than in the previous cases, and averages up to a speed of nearly 300m/s. However, as a result of the injection after the throat, the particles residence time within the carrier gas jet flow is lower in comparison with the other two setups. As a consequence, CFD results suggest that particles can travel approximately 1.5 times slower.

The configuration3 setup was therefore experimentally tested with tin as feedstock powder material (Sandvik Osprey Ltd. SC10 -32+10µm spherical), which was sprayed to form a track onto a polymer substrate in this case (PC/ABS blend). Figure 11(b) shows results observed with such arrangement. The average track width was 2.9mm, against a computational prediction of 1.6mm. Theoretical forecasts therefore underestimate the particles beam size in this configuration. A reason for such behaviour could rely upon particle to particle interactions, which may be not negligible when the particles beam becomes narrower. In fact, particle trajectories would get very close one to the other, resulting in probable contact and subsequent dispersion due to rebounding effects. A simulation of these circumstances can be achievable with full multiphase capabilities suitable for supersonic flows, with implemented algorithms based upon Eulerian methods for particles interactions; however not available in the numerical code used in this analysis.

5 CONCLUSIONS

Cold Gas Spray (CGS) is a novel coating technology, based upon supersonic impacts of particles upon a substrate material, accelerated by a carrier gas within a nozzle. The design of the supersonic nozzle implemented in the system is critical with respect to process efficiency and coating geometry. In this paper, three nozzles configurations were examined, characterized by a different acceleration channel lengths and powder injectors geometry and locations. When powder is released axially and upstream the nozzle throat, particles trajectories do not stay close to the centreline, but tend to spread over the entire volume of the channel. The particle stream diameter at impact with substrate is comparable with the nozzle exit cross-section diameter. A theoretical (CFD) analysis has shown that one of the reasons for this effect is a relatively high gas turbulence level generated at the vicinity of the nozzle throat. The beam geometry by the CFD results compares well against experimental observations. On the other hand, when powder is released axially and straight into the supersonic region of the nozzle, a more focused stream can be achieved. In this particular case, CFD results were in accordance with the experiments, but failed to provide an accurate prediction of the powder beam geometry. Further software developments are therefore needed in order to validate the use of numerical methods for a wider number of Cold Gas Spray applications.

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