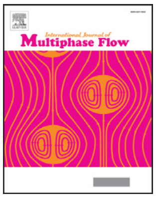
International Journal of Multiphase Flow 000 (2018) 1–15

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow



Particle velocity and dispersion of high Stokes number particles by PTV measurements inside a transparent supersonic Cold Spray nozzle

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ARTICLE INFO

Article history:
Received 22 June 2017
Revised 23 May 2018
Accepted 23 May 2018
Available online xxx

Keywords:
Supersonic nozzle flow
Particle laden flow
High Stokes number
Nozzle-internal
Particle tracking velocimetry
Particle loading
Cold Spray

ABSTRACT

The complexity of technical applications involving particle-laden gas flows often impedes a holistic understanding of the interplay of underlying physical aspects. The usual approach is to isolate phenomena and study them individually, forcing researchers to ignore realistic circumstances. An example is the coating formation process Cold Spray (CS), in which high Stokes number particles are accelerated in a supersonic nozzle and free jet. Along the flow, the particle laden gas undergoes extreme changes, e.g. in velocity, temperature and volume fraction, through a series of interconnected flow events for a poly-disperse distribution of particle sizes. A consequence of this complexity is an under-representation of research on the fluid-mechanics in this field. This manuscript aims to build a bridge between empirical testing in CS and more fundamental aspects of the relevant fluid mechanics: Parameters associated with the multi-phase character of the process are not yet well understood. In this sense, the particle mass loading is often ignored, so are particle-particle interactions and the strong variations of local conditions. Previous work has indicated that there is no conclusive understanding of the phase interaction mechanisms in CS beyond high-Mach number drag laws. In order to start filling this gap, the first experiment for the direct observation of the particle behaviour within a CS nozzle is designed. Rectangular de-Laval nozzles are manufactured from quartz glass and particle tracking velocimetry (PTV) is used to obtain particle velocities and positions at the injection zone, throughout the nozzle and in the supersonic jet under varying operating conditions. This study firstly reports the direct measurement of particle injection, acceleration, and dispersion in CS. It suggests physical explanations based on a statistical evaluation of the observed data and forms the basis for more fundamental understanding of CS fluid mechanics.

1. Introduction

Technical applications involving particle-laden gas flows are generally complex and therefore studied by empirical parameter variations rather than fundamental analysis of the physical phenomena. An example of such problems is the coating formation process Cold Spray (CS). Increasing attention is paid to this process, because it minimizes disadvantages of particle melting and hence provides a possibility to coat progressive material combinations (e.g. oxidisation-sensitive materials, materials with different melting temperatures Alkhimov et al., 1990; Papyrin, 2001). The working principle of CS is easily explained and is illustrated in Fig. 1(a) high pressure process gas is fed into a converging-diverging nozzle, expands and emerges as a supersonic jet. A secondary stream of (carrier) gas is led through a powder feeder, forming a gas-particle mixture, which is then injected into the subsonic region of the process gas. The particles accelerate to velocities of several hundred metres per second in the jet. This kinetic energy is used for the coating deposition by impinging the jet onto a substrate, leading to melt-free deformation and bonding of the particles. For this to succeed, a material-specific critical impact velocity must be crossed, which makes the multi-phase flow, in particular particle acceleration, the most critical aspect of the technology (Assadi et al., 2003; Grujicic et al., 2004). The gas-particle mixture undergoes extreme changes in many properties, such as velocity, temperature and volume fraction: a rather dense plume with volume fractions up to 0.1% at particle Stokes numbers between 10 and 1000 at the injection, an (internal) dispersion in strong co-flow (main process gas), and after acceleration and emission from the nozzle exit, a compressible jet at particle volume fractions reduced by at least two orders of magnitude. Considering the interplay of these subsequent processes is hereby important, since the connection of this series of events has direct technical relevance. Although some aspects are strikingly similar to other processes, explanations of observed phenomena are usually provided by separate studies that isolate specific conditions and individually analyse them. Possible interactions

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https://doi.org/10.1016/j.ijmultiphaseflow.2018.05.018
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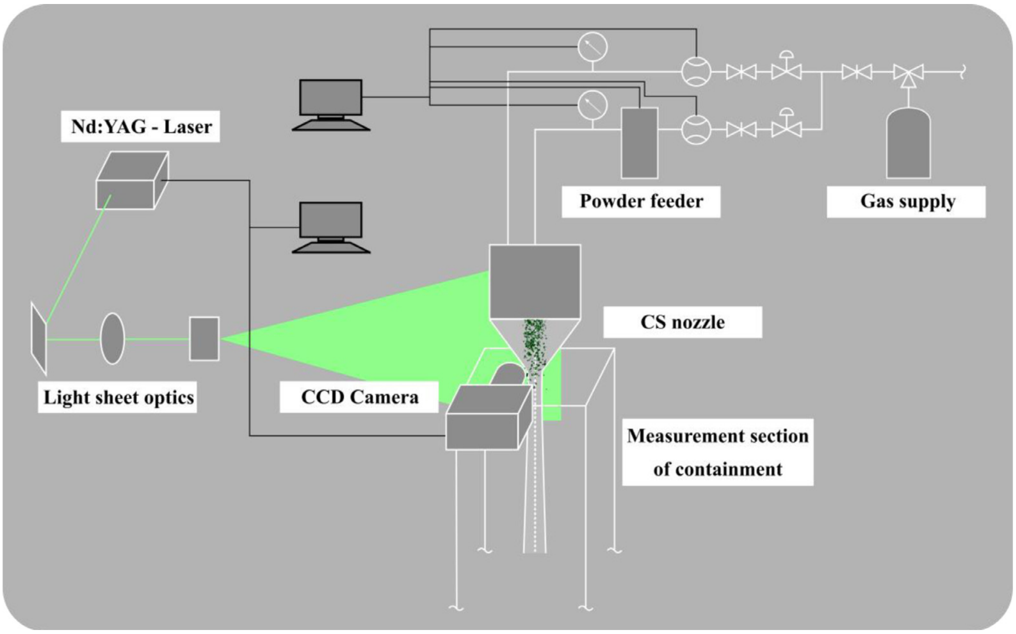

Fig. 1. CS process and measurement set-up.

of these isolated aspects are very difficult to integrate and hence usually ignored.

For example, in CS-related research, both experimental and numerical studies on the particle-laden gas flow in the jet region were conducted in the past decades, in order to identify the main parameters for particulate acceleration. This way, the gas stagnation pressure and temperature (Han et al., 2005; Kwon et al., 2005), the gas species (Jen et al., 2005; Katanoda et al., 2007), powder injection conditions (Yin et al., 2014a,b) and particle material and size (Gärtner et al., 2006; Sova et al., 2013; Li et al., 2011), as well as shape (Wang et al., 2011; Li and Li, 2004) were found crucial. Because such studies seldom connect their findings to work on the fundamentals of fluid mechanics, only few of these aspects are understood. For instance, no connections are made to particle laden flows in pipes (Alletto and Breuer, 2013), dispersive shear flows (Gualtieri et al., 2013), or particle dispersion in jets (Calvo et al., 2016; Sun et al., 2017), while fundamental research in these areas is still ongoing. A reason is that in such studies, important conditions cannot be simultaneously met, e.g. the velocity range, or the particle size range. Likewise, studies on compressible free jets are still in process and frequently deliver new insights, for example on the effect of shock and expansion structures in the supersonic regime on the jet self-similarity and mean Mach number distributions (De Gregorio, 2014). Also compressible rectangular jets are subject to analysis of mixing and the development of shock-structures depending on their aspect ratio (Valentich et al., 2016). Another aspect relevant for CS research is the inter-particle collision in a nozzle and jet flow that leads to manipulated particle dispersion; some studies address such aspects (Volkov et al., 2005), in which effects of increasing Stokes numbers and polydispersity on collision frequencies (Yan et al., 2008) have particular relevance for CS.

Nonetheless, knowledge that emerges from such work is rarely found in CS literature, being difficult to transfer insights. While Schlieren imaging is possible (Samareh et al., 2009), it is generally impossible to measure the gas phase with the solid phase present in a quantitative manner. In some applications, low concentrations and adequate sizes of droplets allow for advanced measurement procedures that can reach such goals (Hardalupas et al., 2010), but in case of CS, the solid phase is not combinable with tracers for the gas phase. Although this problem remains unsolved, advanced techniques, such as 3D astigmatic particle tracking velocimetry (PTV), can deliver astonishing details about the particle trajectories and impacting conditions, which approach the acceleration process in CS (Buchmann et al., 2014). However, it is required to change the set-up and therefore, invoke significant differences from the process conditions. One main issue is that the measureable locations are restricted to the jet, while the particle acceleration and phase interaction mechanisms take place within the CS nozzle. Consequently, the most crucial part of the process is inherently confined to indirect measurements. A long tradition of such can be reviewed in literature and was recently summarised along with their importance for numerical methods in CS by our research group (Yin et al., 2016): Schlieren photography was frequently used along with several quantitative measurement methods: laser-two-focus (L2F) (Gilmore et al., 1999), doppler picture velocimetry (DPV) (Fukanuma et al., 2006), and lastly particle image velocimetry (PIV) or similar techniques, in particular particle tracking velocimetry (PTV) (Jodoin et al., 2006; Raletz et al., 2006; Ning et al., 2010). While these studies focus on measurements of the particle conditions upon or shortly prior to deposition, direct nozzle-internal observations that assess the particle velocity and dispersion throughout the process were not attempted, due to the difficulty of the experiment design. A first turn was taken by Katanoda et al. (2007), who used flow visualisation in a constant area barrel that extended a de-Laval nozzle for CS applications. Again, outside of CS it was shown that flow structures within converging-diverging nozzles are measureable in great detail by elaborate Schlieren imaging design (Giglmaier et al., 2014).

With raised discrete phase loading (e.g. pursuing lower production cost Stier, 2014), the particle acceleration process is increasingly affected. The flow is in a dense-dilute transitional regime, where it is not predetermined what mechanisms are irrelevant. CS literature hence shows some ambiguity on the respective parameter variations. Some found the particle feed rate to be without influence (Pardhasaradhi et al., 2008; Schmidt et al., 2009), some show the contrary (Samareh et al., 2009; Meyer and Lupoi, 2015). Computational analysis showed that a momentum coupling can reproduce the trend of decreasing velocities with feed rate, nevertheless fails to provide reliable quantitative results, suggesting that

Please cite this article as: M. Meyer et al., Particle velocity and dispersion of high Stokes number particles by PTV measurements inside a transparent supersonic Cold Spray nozzle, International Journal of Multiphase Flow (2018), https://doi.org/10.1016/j.ijmultiphaseflow.2018.05.018