# SENSITIVITY STUDY OF DUST-LADEN FLOWS IN THE DLR GBK FACILITY USING THE DUST-US3D FRAMEWORK

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## ABSTRACT

An unstructured integrated simulation framework DUST-US3D has been used to study particle-laden flows in the German Aerospace Center (DLR) GBK facility. Air/particle inflow conditions and the overall simulation methodology has been adjusted to ensure consonance with recent experimental work. The resulting particle dynamics are found to be extremely sensitive to the configuration of the particle injection process. However, owing to relatively low particle mass flow rates incorporating 2-way coupling (particles-gas exchange momentum/energy) or particle-particle collisions has no significant impact on predictions. Numerical estimates for particle velocity magnitude are consistently lower than those observed during experiments which could be indicative of particles coalescing into larger, possibly non-spherical aggregates.

***Index Terms—*** Particle-laden flows, GBK, DUST-US3D

## 1. INTRODUCTION

A steady increase in mission complexity over the years culminating in future crewed landings has necessitated an improved characterization of hypersonic entry through the Martian atmosphere. A potential threat to spacecraft during hypersonic descent is dust suspended in the planetary atmosphere. The level of dust – both number density and the maximum altitude at which it can be found – significantly increases during major dust storms. The degradation suffered by spacecraft thermal protection systems (TPS) due to dust particle impacts can be comparable to that from thermochemical ablation [1, 2]. The presence of particles in a spacecraft's immediate surroundings can trigger a multitude of changes. These can range from direct effects such as TPS erosion and augmented surface heat flux due to particle-wall collisions to more indirect phenomena such as modification of the radiation field or flow transition due to cratering of the spacecraft surface. Multiphase flows would also be encountered in other spaceflight missions such the entry of Dragonfly spacecraft through the Titan atmosphere (organic haze particles) or retropropulsive landings which can eject regolith due to plume-surface interaction (PSI) [3]. The unpredictability of weather phenomena such as planet sweeping dust storms coupled with long travel times for typical planetary missions makes it imperative that the design process account for the possible damage caused by dust particles impacting an entry vehicle.

Motivated by these requirements, the Entry Systems Modeling (ESM) project under the NASA Game Changing Development (GCD) program and the German Aerospace Center (DLR) have entered into a collaboration to deliver state-of-the-art numerical and experimental assessment of particle-laden high-speed flows. There is particular focus on updating outmoded legacy databases along with establishing appropriate computational/experimental methodologies for accurately predicting vehicle characteristics in such a multi-physics environment. A key pillar of this effort is the DLR GBK facility [4] which incorporates sophisticated diagnostic techniques for simultaneous measurement of particle size, velocity, and mass flow rate. The high-fidelity data being made available through the GBK facility is spatially-resolved instead of being limited to basic, aggregated quantities and would enable deeper insights into particle dynamics.

These experimental advances are being complemented by the development of a new simulation framework for modeling dusty flows. The components of this framework are two-fold, a Lagrangian particle code titled DUst Simulation and Tracking (DUST) which works in conjunction with one of NASA's flagship unstructured, finite-volume flow solvers, US3D. The current work presents a preliminary sensitivity analysis using the DUST-US3D framework of particle flows in the GBK facility. This includes examining the effect of particle-flow and particle-particle interactions on various particle-related quantities-of-interest (QoIs) and comparing numerical predictions with recent experimental data. The remainder of the paper is organized as follows: a) Section 2 presents an overview of the GBK facility and the suite of measurements obtained from it. b) Section 3 summarizes the DUST-US3D framework. c) Section 4 discusses the impact of particle-flow coupling (2-way coupled simulations) and particle-particle collisions in the GBK facility. This is followed by a detailed analysis of 1-way coupled particle simulations (particles are influenced by the carrier gas but the not the other way round). d) Conclusions are discussed in Section 5.

## 2. GBK FACILITY

The multi-phase flow facility (GBK) is a small test facility located within DLR's supersonic wind tunnel complex in Cologne, Germany [4]. It is a fully automated blow down facility where high-pressure air from reservoir tanks accelerates through an ideal-contoured Ma=2.1 de Laval nozzle. The test gas used in the facility is air and is split into a heated "main" flow and an unheated "bypass" flow. Particles are seeded into the "bypass" flow and get injected into the mixing chamber along with the test gas. The maximum design pressure and maximum total air flow rate are 5.4 MPa and 1.5 kg/s, respectively. An instrumented probe, typically a cylinder with a hemispherical-shaped tip, is mounted on a fast flow probe insertion system and can be positioned at a fixed distance downstream of the nozzle exit.

A raft of improvements have been made to the GBK facility with regards to non-intrusive measurement of particle characteristics [4]. Particle size and velocity can now be simultaneously determined using shadowgraphy techniques. Furthermore, particle velocities can be obtained for a large field-of-view (FoV) using particle tracking velocimetry (PTV) cameras. This is combined with velocity-diameter correlations from shadowgraphy to estimate particle size as well. Additional details regarding the methodology, measurement uncertainty, and experimental constraints can be found in [4]. The current work compares numerical predictions with experimental data that was obtained for $Al_2O_3$ particles. The density of $Al_2O_3$ was set equal to 3950 kg/m$^3$. The $Al_2O_3$ particles prior to being used in the GBK facility were examined using dynamic image analysis and laser diffraction. This yielded the probability distribution of particle diameters for the polydisperse mixture. The same distribution function is utilized in the numerical calculations to define the size of particles being introduced into the domain.

## 3. DUST-US3D PARTICLE-FLUID FRAMEWORK

The US3D code [5], developed at the University of Minnesota in collaboration with NASA Ames Research Center, solves the chemically reacting non-equilibrium Navier-Stokes equations for unstructured grids using the implicit data-parallel line-relaxation method. It provides a range of implementations for handling thermochemical properties, turbulence, and numerical flux reconstruction. The standard approach (the same has been used during the present work) is based on modified Steger-Warming flux splitting with second-order accurate MUSCL extrapolation and Min-Mod limiter. The US3D code is used widely at NASA and has been applied to a range of aeronautical and aerothermal flow problems.

The DUST solver treats the dispersed particle phase in a Lagrangian manner, providing time-accurate solution of particle location, velocity, temperature, and diameter. It uses the point-particle discrete element method to track the dynamics of large populations of particles traveling through a three-dimensional domain. The DUST solver adopts a variable-fidelity paradigm. This allows modeling complexity to be adjusted based on the level of realism being sought for describing particle-fluid and particle-particle interactions. The entire gamut of particle-fluid coupling – 1-way (carrier gas influences particles), 2-way (both carrier gas and particles exchange momentum/energy), and 4-way (2-way coupling while also accounting for particle-particle collisions) – can be seamlessly dealt with within the same framework. Consequently, QoIs such as surface heat augmentation and erosion due to particle impacts can be comprehensively characterized for a wide range of physical conditions.

A concerted effort has been made to incorporate numerical strategies that offer a balance between computational tractability and accuracy. A core component underpinning the solver is the particle mesh-localization algorithm that relies on standard mesh-connectivity information to identify the sequence of Eulerian cells that particles traverse during a time-step. The choice of this procedure also simplifies subsequent operations pertaining to enforcement of boundary conditions, point-to-point parallelization over a distributed memory system, and determining back-coupling source terms for the surrounding flow. The time-driven hard-sphere approach is leveraged to accelerate evaluation of particle-particle collisions. Time-integration has been performed using Adams-Bashforth that ensures high temporal accuracy at limited computational costs. A wide range of multi-phase problems have been investigated using the DUST-US3D framework including both verification tests involving hypersonic planetary entry, flow through converging-diverging nozzle, and impingement of dust particles on a flat plate and mission-relevant analysis such as heat-flux augmentation due to particle impacts on the Mars 2020 spacecraft.

The current analysis assumes all particles are perfect spheres. The Henderson model and Fox correlation are used to compute drag coefficients and Nusselt numbers, respectively. Additional details on physical models, numerics, and algorithmic choices can be found in [6]. More recently, the ability to inject polydisperse particle mixtures based on stipulated diameter distribution functions through inexpensive inverse transform sampling [7] has been added to the DUST solver.

## 4. RESULTS

This section summarizes computational results obtained for multiphase flows in the GBK facility using the DUST-US3D framework. The boundary conditions for the pure gas flow have been set in order to replicate experiments test conditions employed in [4]. An iterative procedure is employed to achieve this. First, a Mach number value for the "main" flow entering the mixing chamber is assumed. Then, quasi one-dimensional relations are employed to calculate flow conditions from experimentally reported total pressure and temperature values. Concurrently, inflow velocity is computed based on the experimental mass flow rate and the previously determined density. The Mach number value is adjusted till the inflow velocity from the two approaches becomes consistent. The flow conditions for “bypass” air entering through the injector have been computed using experimental data for mass flow rate, pressure, and temperature. The freestream values enforced at the inflow faces for mixing chamber (“main”) and injector (“bypass”) are listed in Table 1.

Although polydisperse injection of spherical $Al_2O_3$ particles is performed based on the cumulative particle number distribution from [4], the range of diameters is restricted to $[3.5, 67.4]$ $\mu$m. The particles enter the domain equilibrated with the “bypass” flow. However, in order to facilitate homogenization the injection velocity direction for fresh particles is picked randomly [8]; only directions that send the particles into the domain are considered. Since the focus of this study is on establishing a preliminary insight into the phenomenology of particle-flow interactions in the GBK only a rough approximation for the particle mass flux density $G_P$ is used. This value, estimated to be $1.294$ kg/(m$^2$s), is based on the average particle discharge rate observed during experiments and is applied uniformly on the injector face.

**Table 1**: Flow properties enforced at the chamber entrance and injector opening, respectively.

| Air | $\lvert \boldsymbol{u}_{c,\infty} \rvert$ [m/s] | $\rho_{c,\infty}$ [kg/m$^3$] | $T_{c,\infty}$ [K] |
|---|---|---|---|
| “Main” | 22.3 | 8.81 | 372.9 |
| “Bypass” | 55.3 | 11.49 | 290.1 |

In order to improve computational tractability, the problem is assumed to be symmetric perpendicular to the injector and chamber axes. Consequently, only half of the three-dimensional domain ($z > 0$ m for this study) is considered, resulting in a mesh with approximately $1.8 \times 10^6$ hexahedral cells. Symmetric conditions are applied along the centerline plane, $z = 0$ m. All walls inside the facility are considered to be isothermal with temperature fixed at 290 K. Supersonic outflow is imposed on domain boundaries at the test chamber exit. Details regarding restitution and friction coefficients acting during particle-wall collisions and particle-particle collisions can be found in [6].

The variation in the axial velocity component of the pure gas flow along the symmetry plane is presented in Figure 1. The flow rapidly accelerates through the converging-diverging nozzle, attaining an axial velocity of approximately $540$ m/s at the nozzle exit located at $x = 0$ m. A detached bow shock is formed ahead of the test-specimen resulting in a sudden drop in velocity/rise in temperature. Subsequently, as the flow moves past the shoulder of the specimen it undergoes rapid expansion and reattains pre-shock velocities. The

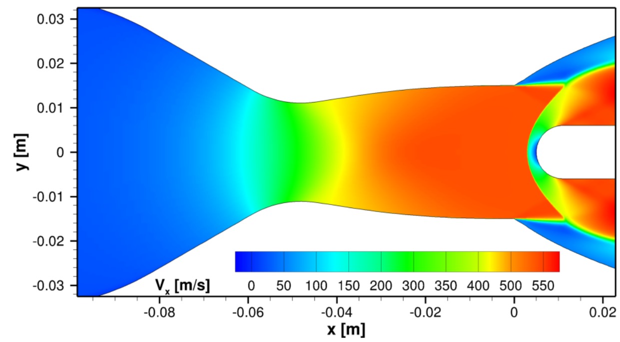


**Fig. 1**: Axial velocity for the pure-gas flow along the $z = 0$ m plane through the GBK nozzle and test chamber.

corresponding 1-way coupled particle-flow simulations are visualized by plotting instantaneous particle locations in Figure 2. Particle sizes are scaled based on their diameter values which allows the polydisperse nature of the particle phase to be observed clearly. Particles enter transverse to the chamber axis through the injector. The smaller-sized particles due to lower inertia adjust quickly to the surrounding flowfield and are swept axially in the cross-flow. However, the larger-sized particles can withstand gas-induced retardation to a greater extent and may even strike the diametrically opposite section of the facility wall before they begin traveling downstream. Numerical experiments indicate that random assignment of particle inflow directions is paramount to ensuring that a more uniform distribution of particle diameters is obtained in the mixing chamber and minimizing bias in downstream QoIs.

### 4.1. Impact of 2-Way Coupling and Particle-particle Collisions

A key point of inquiry during this study was the possible impact of momentum/energy transfer between phases during 2-way coupled simulations on particle and flowfield characteristics. Additionally, an attempt was also made to quantify the role particle-particle collisions could play in shaping relevant QoIs. In the case of 2-way coupled calculations, particles were injected starting from a steady state pure-gas solution (the same flowfield used for 1-way coupled analysis). Simulations were run till statistical convergence for QoIs under consideration was achieved. Figure 3 presents the difference in axial velocity $V_x$ when switching from a pure-gas flow to a 2-way coupled multiphase flow (the nozzle exit is marked as a dashed vertical line). The injected $Al_2O_3$ particles, especially the larger ones, cannot accelerate as rapidly as the surrounding flow while transiting through the nozzle. Consequently, they drain kinetic energy from the gas phase resulting in the largely negative values for $\%\Delta V_x$ throughout the domain. However, deviation from the pure-gas flowfield state is minimal and $|\%\Delta V_x| < 2.5\%$ for the nozzle section. The average mass loading $\beta$, *i.e.*, the ratio of total particle to

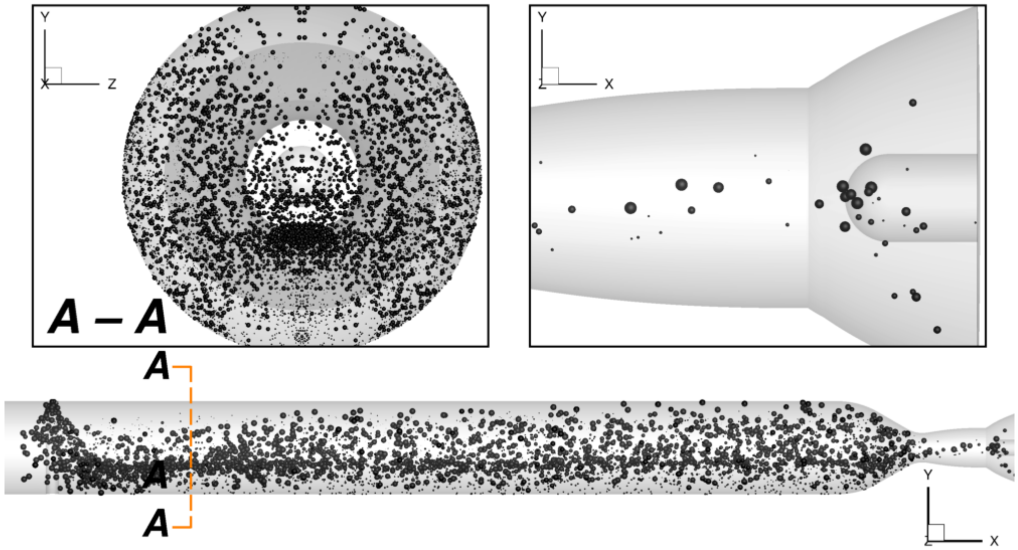


**Fig. 2**: Instantaneous particle locations in the GBK facility for 1-way coupled flows. Particle size is scaled based on its diameter.

air mass densities, once the particles have spread throughout the mixing chamber is approximately $1.2\%$. This value remains low due to the relatively large dimensions of the mixing chamber and the high mass of the combined "main" and "by-pass" air flow. Previous studies [6] also suggest that $\beta$ within such a range might not be sufficient to engender pronounced changes in flow structures. Experimental measurements in

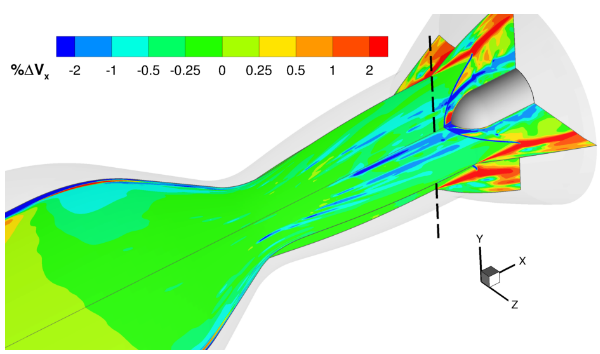


**Fig. 3**: Percentage difference in axial velocity between the pure-gas and 2-way coupled multiphase flows.

the GBK facility [4] have been performed along the symmetry $x - y$ plane located at $z = 0$ m. Furthermore, the variation in particle-related quantities have been reported along the nozzle exit. It is important to note that the FoV for techniques such as shadowgraphy and PTV is discretized into cuboidal volumes-of-interest (VoI) with pre-defined dimensions. The contribution of all particles occupying a given VOI, both for instantaneous and temporal averaging, is considered to then obtain the spatial variation in particle QoIs. Data from numerical simulations has been post-processed to maintain congruency with the experimental methodology, requiring individual particles to be bundled into relatively coarse VoIs matching those for shadowgraphy and PTV. The variation in particle mass flux density $G_{\mathrm{P}}$ and average velocity magnitude in the measurement plane $V_{\mathrm{P}}$ along the nozzle exit are presented in Figure 4. In addition to 2-way coupled simulations, calculations have also been performed with 1-way coupling but while accounting for particle-particle collisions. The three sets of results for $G_{\mathrm{P}}$ and $V_{\mathrm{P}}$ exhibit similar characteristics which is a direct consequence of the low $\beta$ prevailing in the domain. There are some noticeable differences corresponding to isolated VoIs but those could emanate from under-sampling during temporal averaging especially for the computationally intensive 2-way coupled calculations.

### 4.2. Detailed analysis of 1-Way Coupled Calculations

The initial focus of the present study was on assessing if computationally onerous 2-way coupling or particle-particle collisions could significantly perturb particle-flow dynamics. Once their role was assessed to be minimal, a more detailed analysis employing the far more inexpensive one-way coupling without inter-particle collisions was performed and compared to experimental data. Results based on this approach are referred to as "1-Way" and an explicit mention of particle-particle collisions being ignored has been dropped for brevity. The numerically computed radial variation in $G_{\mathrm{P}}$, $V_{\mathrm{P}}$, and average particle diameter $D_{\mathrm{P}}$ along with previously reported PTV measurements from experimental run N11 [4] are plotted in Figure 5. The simulations yield higher spikes in $G_{\mathrm{P}}$ as compared to experiments. However, this is possibly an outcome of the rough estimate for $G_{\mathrm{P}}$ at the injector face which was not directly measured during experiments but inferred from facility operating characteristics. On the other

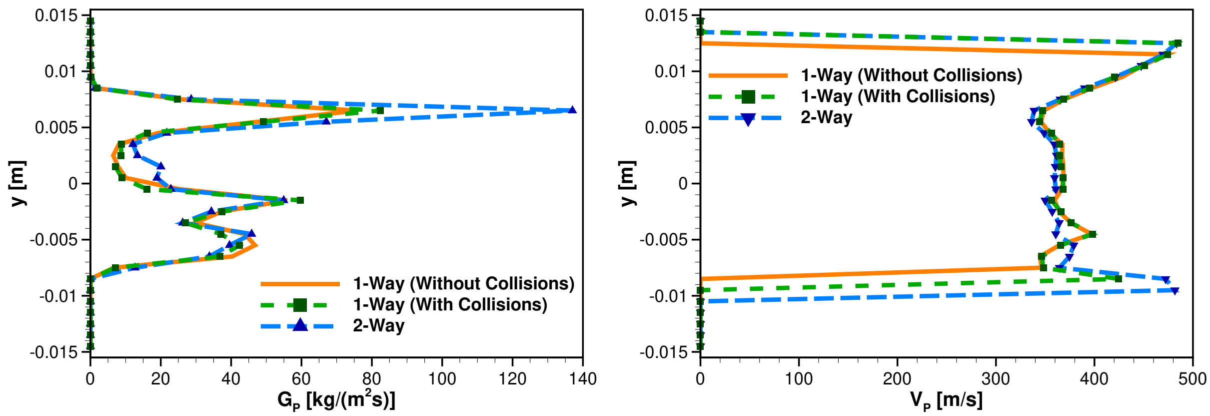


**Fig. 4**: Particle mass flux density (left) and average in-plane velocity magnitude (right) along nozzle exit with $z = 0$ m for 1-way coupled flows without and with collisions and 2-way coupled flow.

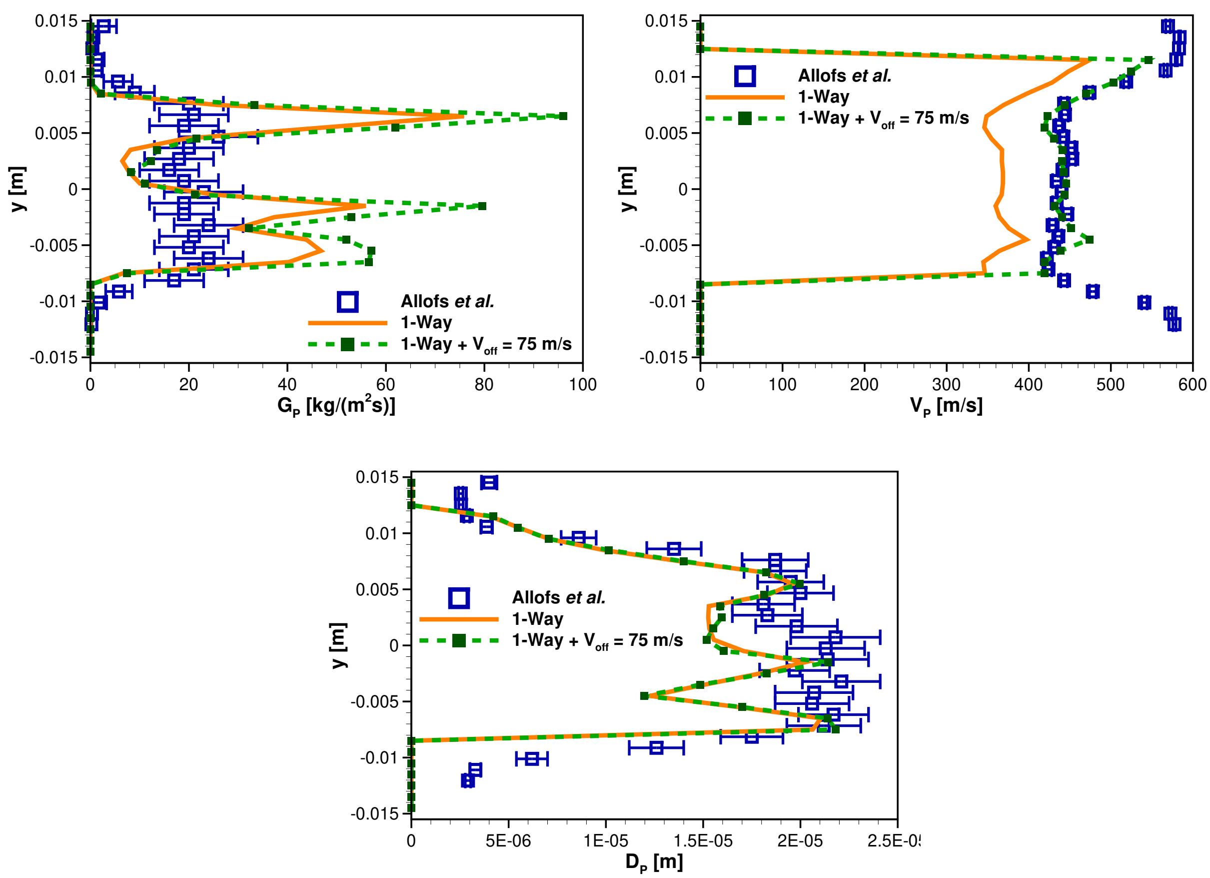


**Fig. 5**: Particle mass flux density (top-left), average in-plane velocity magnitude (top-right), and average particle diameter (bottom) along nozzle exit with $z = 0$ m for 1-way coupled flows without and with an artificial velocity offset $V_{\text{off}} = 75$ m/s. Experimental PTV data from [4] is also presented.

hand, quantities such as $V_{\text{P}}$ and $D_{\text{P}}$ are based on sampling the unsteady particle solution at a prescribed frequency, identifying particles instantaneously occupying different VoIs, and then performing a temporal, VoI-wise average. These average quantities are less sensitive to the total injected particle mass flow rate and reflect fundamental particle dynamics when

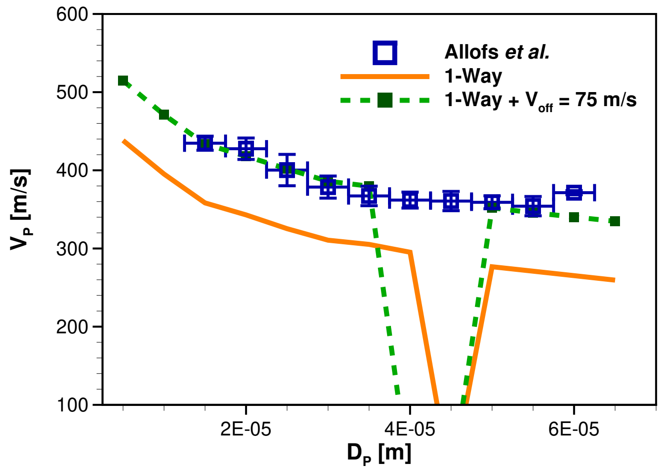


**Fig. 6**: Change in in-plane particle velocity magnitude with particle diameter for a VOI centered at $x = y = z = 0$ (intersection of axis and nozzle exit). Results include those for 1-way coupled flows without and with an artificial velocity offset $V_{\rm off} = 75$ m/s and experimental shadowgraphy [4].

operating in a certain physical regime. Consequently, they are more amenable to comparisons with experimental data. In similar vein, Figure 6 outlines the relationship between the in-plane particle velocity magnitude and particle diameter for a VOI centered at $x = y = z = 0$ (intersection of axis and nozzle exit). It also presents experimental measurements obtained using shadowgraphy [4]. Particles appear to attain lower velocities when they arrive at the nozzle exit in the numerical simulations in contrast to the experimental data. Similar behavior has also been reported in previous work on the GBK [4]. The authors had to artificially decrease the particle density by over $50\%$ in order to achieve better agreement with the shadowgraphy $V_{\rm P}$ vs $D_{\rm P}$ data. One possible justification for this could be that particles form aggregates which incorporate large voids leading to an effective reduction in particle density. Another mechanism for realizing higher acceleration of particles in the nozzle section is linked to increasing the drag coefficient $C_D$ (and the resulting drag force). Numerical experiments during the course of the present work suggest that a two-fold rise in $C_D$ allows improved reproduction of experimental trends. This change can be attributed to non-spherical nature [9] of particles or the aggregates they form while traveling through the facility. These effects will be delved into greater detail during future studies. The current work introduces a simple velocity offset $V_{\rm off}$ which is added to the in-plane velocity magnitude only while particle statistics are being computed., *i.e.*, without altering the particle solution or time-integration. Results obtained with $V_{\rm off} = 75$ m/s match well with PTV/shadowgraphy data. As expected, the choice of $V_{\rm off}$ has no bearing on the average diameter distribution. The sharp jumps observed in Figure 6 for certain diameter values are due to undersampling with no particles in the relevant diameter range being detected in the VoI.

## 5. CONCLUSIONS

The unstructured particle-flow simulation framework DUST-US3D was used to investigate particle-laden flows in the DLR GBK facility. Emphasis was placed on replicating conditions – amongst them air inflow state, particle polydispersion, and sufficient particle-flow homogenization – observed during recent experimental campaigns. Additionally, particle statistics were computed by establishing a FoV around the nozzle exit and discretizing it into VoIs in a manner analogous to the experimental methodology. The current analysis indicates that the level of particle mass loading under consideration is not adequate for fostering prominent changes in the carrier gas during 2-way coupled simulations. In similar vein, the introduction of particle-particle collisions also has a negligible impact on particle dynamics. Thus, an inexpensive 1-way coupling between the particle and gas phase is sufficient for characterizing the flow through the GBK facility. A key inconsistency with respect to the experimental data relates to particles attaining lower velocities at the nozzle exit. Previous work on the subject has speculated that this could stem from the formation of aggregates which can potentially decrease particle density and/or augment drag coefficient due to non-sphericity. A simple, constant velocity offset value of 75 m/s has been introduced in the present work in the way of improving correlation with experimental measurements. Future work will entail assessing the aggregate formation hypothesis and a further refinement of modeling parameters/conditions based on new experimental data that is made available.

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