

# Particle-turbulence interaction of high Stokes number irregular shape particles in accelerating flow: a rocket-engine model

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## Abstract

Metal particles in solid propellants enhance rocket engines performance. An interaction of particles with a high Reynolds number turbulent gas flow accelerating to a nozzle, has not been characterized thoroughly. We study the particle-turbulence interactions in a two-dimensional model of a rocket engine. Two-phase particle image/tracking velocimetry provides the flow velocity simultaneously with the velocities of irregularly shaped inertial particles ( $d_p \sim 320\mu\text{m}$ , Stokes  $St \sim 70$ , particle Reynolds number  $Re_p \sim 300$ ). We reveal the local augmentation of turbulent fluctuations in the particle wakes (up to 5 particle diameters downstream the particle). Despite the low mass fraction, the large response time of the particles leads to an increase of turbulent kinetic energy (TKE) everywhere in the chamber. The increase of local particle mass fraction near the nozzle, due to the mass conservation and converging streamlines, compensates for the dampening effect of the strong mean flow acceleration and further augments TKE at the nozzle inlet. Furthermore, this is accompanied by unexpectedly isotropic fluctuations in the proximity of the nozzle. The phenomenon of the isotropic, strongly enhanced turbulence in the proximity of the engine nozzle achievable with the low mass fraction of high  $St, Re_p$  particles, can be used to improve the design of solid propellant rocket engines.

Keywords: Particle laden turbulent flow, Rocket engine, Turbulence modulation, Spatial acceleration

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## 1. Introduction

Despite a vast body of research on the dynamics of dispersed particles in turbulence, we cannot predict whether TKE will be augmented or attenuated in complex flow cases (Balachndar and Eaton, 2010). For instance, apparently similar flow cases were reported to have contradicting trends in studies of particle-turbulence interaction in fully developed channel flows for different sizes and densities of particles Kulick et al. (1994); Kussin and Sommerfeld (2002); Kiger and Pan (2002); Li et al. (2012). Kulick et al. (1994) investigated

9 turbulent flow in a vertical channel and found turbulence attenuation that in-  
10 creased with mass loading and Stokes number. Kiger and Pan (2002) showed  
11 turbulence augmentation far from the wall and negligible effect near the wall.  
12 Kussin and Sommerfeld (2002) found significant turbulence augmentation near  
13 the channel center plane for particles larger than  $\eta$  with particle Reynolds num-  
14 bers above 350, and turbulence attenuation near the wall. Conversely, Li et al.  
15 (2012) found increased fluctuations near the wall and reduced fluctuations in the  
16 outer region of the boundary layer. Cisse et al. (2013) developed a fully resolved  
17 direct numerical simulation around a relatively large particle at moderate parti-  
18 cle Reynolds numbers, and using conditional analysis in the coordinate system  
19 relative to the particle position, have shown that particles reduce fluctuations  
20 in their wake. The authors presented particle fluid coupling at distances of one  
21 particle diameter and that a particle essentially creates a “shadow in its wake”.  
22 At larger particle Reynolds numbers, Hetsroni (1989) found an augmentation  
23 of TKE. The authors explained this by the vortex shedding mechanism in the  
24 wake of the particle. These examples are by no means a comprehensive review  
25 of the existing literature. It is a small sample emphasizing that a small vari-  
26 ation of parameters, along with the carrier phase flow and particle properties,  
27 can produce substantially different effects of particles on the TKE.

28 Particle-fluid flow interaction is characterized by the ratios of a) length  
29 scales, namely, the size of the particle relative to the relevant flow length scale,  
30 b) time scales, i.e., particle response time relative to the relevant flow time scale,  
31 or the Stokes number, c) particle Reynolds number,  $Re_p$ , based on the relative  
32 (sometimes called slip) velocity (Hetsroni, 1989; Tanaka and Eaton, 2008):

$$Re_p = \frac{|\mathbf{U} - \mathbf{V}_p|d_p}{\nu}, \quad (1)$$

where  $d_p$  is the particle diameter,  $\mathbf{V}_p$  is the particle velocity (bold symbols de-  
note vectors),  $\nu$  is the fluid kinematic viscosity, and  $\mathbf{U}$  is a so-called “undisturbed  
fluid velocity at the position of the particle”, which is practically estimated as  
an interpolation of the surrounding fluid velocity to the position of the parti-  
cle (e.g. Meller and Liberzon, 2015). The particle relaxation time  $\tau_p$  for small  
and relatively heavy particles,  $\rho_p \gg \rho_f$  and  $Re_p < 1$  is defined as:

$$\tau_{p,s} = \frac{\rho_p d_p^2}{18\mu} \quad (2)$$

However, for higher  $Re_p$  a non-linear drag force correction is required (Crowe  
et al., 2011):

$$\tau_p = \frac{\tau_{p,s}}{1 + 0.15 Re_p^{0.687}} \quad (3)$$

The Stokes number is the time scales ratio (Crowe et al., 2011):

$$St = \frac{\tau_p}{\tau_f}. \quad (4)$$

33 Large Stokes number  $St \gg 1$  means that particles response time is longer  
 34 than the flow time scale. In this work, the particles are larger than the Kol-  
 35 mogorov length scale ( $d_p > \eta$ ), and heavier than the surrounding fluid ( $\rho_p \gg$   
 36  $\rho_f$ ). Therefore, an appropriate flow time scale is that of the mean flow, i.e.,  
 37  $\tau_f = L/U$ , where  $L$  is a turbulent integral scale.

38 The length scales ratio,  $d_p/L$ , where  $L$  is the integral length scale of turbu-  
 39 lence, was proposed by Gore and Crowe (1989) to distinguish between attenua-  
 40 tion for  $d_p/L < 0.1$  and augmentation for  $d_p/L > 0.1$ .

Separately, the aforementioned ratios of time/length scales could not predict  
 reliably the augmentation or attenuation effect for different flow cases. Tanaka  
 and Eaton (2008) suggested another dimensionless parameter that combines the  
 Stokes number with the flow Reynolds number  $Re_L = UL/\nu$  and turbulence  
 scale separation  $\eta/L$ :

$$Pa = St Re_L^2 (\eta/L)^3 \quad (5)$$

41 The authors (Tanaka and Eaton, 2008) combined empirical data from 80 ex-  
 42 periments and demonstrated that in the range  $10^3 < Pa < 10^5$  there is an  
 43 attenuation of TKE, while for all other cases (below  $10^3$  or above  $10^5$ ) there is  
 44 an increase in TKE due to particles.

45 Gany et al. (1978) photographed aluminized solid propellants under cross-  
 46 flow conditions forming and burning in the form of agglomerates of Al/Al<sub>2</sub>O<sub>3</sub>.  
 47 The primary particles of the order of 10  $\mu\text{m}$  behaved like flow tracers and did  
 48 not exhibit two-way coupling. However, the irregularly shaped agglomerates,  
 49 in the range of 40 to 800  $\mu\text{m}$ , that formed primarily on the surface during the  
 50 burning process, afterwards were detached and carried by the turbulent flow.  
 51 Caveny and Gany (1979) studied the breakup of agglomerates in aluminized  
 52 propellants when the agglomerates burn slowly compared to the residence time  
 53 in the rocket motor. They found that the agglomerates velocity lags in the  
 54 nozzle, cause breakup of sufficiently large agglomerates, and thereby permit  
 55 reasonable combustion efficiency to be achieved. The motion of large irregular  
 56 particles resembling the agglomerates in the turbulent flow and their contribu-  
 57 tion to the TKE balance (augmentation vs attenuation) is the central question  
 58 of this study.

59 In this work, we study experimentally the effect of large, heavy, and irreg-  
 60 ularly shaped particles on the TKE in a simplified model of a rocket engine.  
 61 We reproduce the key features of the mean flow: a) acceleration towards the  
 62 nozzle; b) the shape of the chamber and the converging type of flow through a  
 63 small nozzle throat; and c) particle sizes that correspond to metal agglomerates  
 64 reported in the literature. In this flow, there are competing effects of acceler-  
 65 ation, particle-turbulence interaction, and monotonically increasing local mass  
 66 fraction due to the contracting flow through the nozzle. To what extent various  
 67 mechanisms contribute to the overall increase or decrease of turbulent kinetic  
 68 energy is not yet clear.

69 This two-phase flow case is somewhat different from the aforementioned ones  
 70 also in the sense that the particle residence time in the flow is rather short as  
 71 compared to the particle response time. Due to fluid acceleration towards the

72 nozzle, all the key parameters, the relative velocity, Stokes number, particle  
73 Reynolds number, the fluid Reynolds number, all vary in the Lagrangian sense,  
74 or inhomogeneous in the Eulerian sense. The case is to some extent analogous  
75 to the interaction of large Stokes particles with the near to far-field of the  
76 jets (Prevost et al., 1996), but all the changes occur on time scales shorter than  
77 the particle residence or response time.

78 We used particle image/tracking velocimetry (PIV/PTV) to measure simul-  
79 taneously the velocities of the fluid and particulate phases in two dimensions.  
80 In the most general case, a two-wavelength illumination and imaging would be  
81 necessary to distinguish between the two phases (Elhimer et al., 2017; Poelma  
82 et al., 2006). However, in this case the particles are much larger as compared  
83 to the flow tracers, and a simple PIV system is sufficient to separate the parti-  
84 cles and fluid tracers (Khalitov and Longmire, 2002; Hwang and Eaton, 2006).  
85 Simultaneous measurements allow to estimate the instantaneous slip velocity  
86 using local flow interpolation and to measure TKE, as well as its change in  
87 respect to the location of particles.

## 88 2. Experimental details

89 We created a quasi-two-dimensional experimental chamber (500 mm long,  
90 245 mm wide, and 35 mm front-to-back wall distance, nozzle throat width is  
91 35 mm) which resembles a cross-section of a generic solid-propellant rocket  
92 motor with round symmetrical cavities (Volkov et al., 2012; Ciucci and Iaccarino,  
93 2012), shown in Fig. 1. The cavities are characteristic of solid rocket motors  
94 with a thrust vectoring system. The back and front walls of the channel were  
95 made from glass for particle imaging and the side walls have optical windows to  
96 enable optical access for the laser sheet. The purpose is to create a quasi-two-  
97 dimensional velocity field as a proxy of the two-dimensional axisymmetric flow  
98 field in a cylindrically shaped rocket engine.

99 The chamber was positioned vertically with the main flow direction and the  
100 particle motion aligned with the gravitational acceleration (Fig. 1a). The air  
101 was supplied by a blower through a converging channel (750 mm above the  
102 measurement region). The measurement volume is  $1L_t \times 1.8L_t$ , the lowest edge  
103 is 40 mm above the nozzle throat, as shown in Fig. 1c. Above this measure-  
104 ment location, the flow resembles the fully developed channel flow with constant  
105 streamwise velocity. Mean streamwise velocity profiles are shown for the two  
106 Reynolds number cases in Fig. 1b. Within the measurement region, the flow  
107 is inhomogeneous in both streamwise and spanwise directions, accelerating and  
108 converging into the nozzle, as shown in Fig. 1d.

109 Olive oil aerosol ( $1 \mu\text{m}$  droplets) produced by a Laskin nozzle seeder, and  
110 alumina particles supplied by a custom-made particle seeder (both manufac-  
111 tured by I.T.E.S Engineering LLC, Israel) were mixed into the air stream before  
112 entering the chamber.

113 We measured turbulent flow and particle motion for two flow rates (low/high).  
114 The Reynolds number at the throat is based on the characteristic velocity de-  
115 fined by the volumetric flow rate through the chamber and the cross-sectional

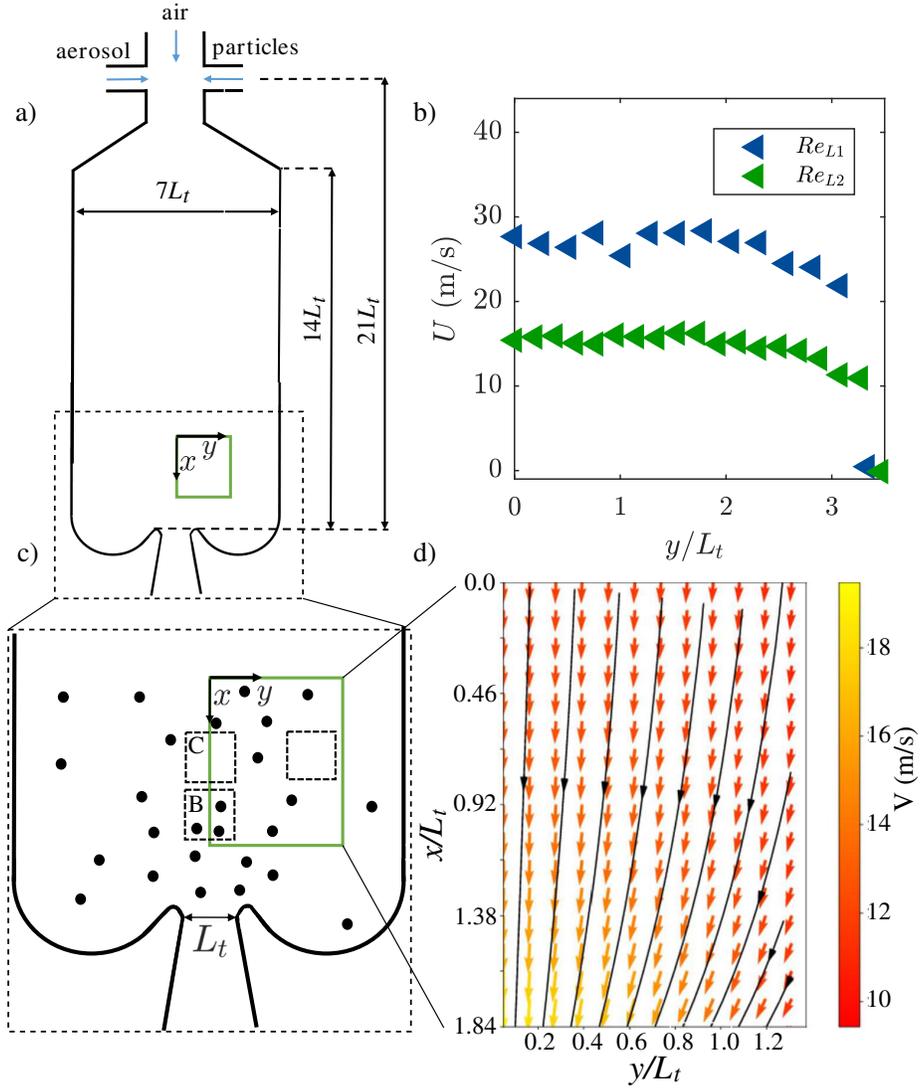


Figure 1: a) Schematic drawing of the rocket engine model setup and PIV region of interest. The coordinate system is defined with  $x$  in the streamwise direction of the mean flow through the nozzle and  $y$  in the transverse direction. The origin is defined on the centerline of the chamber  $2.8L_t$  above the nozzle throat, b) Mean streamwise velocity distribution  $U(y/L_t)$  at  $4L_t$  above the nozzle throat for both flow rates, c) Zoom in view of the measurement region of  $1L_t \times 1.8L_t$ , d) Mean flow velocity field and streamlines in the measurement region.

116 area of the nozzle. The Reynolds number at the throat is  $Re_L = 185,000$  and  
117  $260,000$ , for the low and high flow rates, respectively. In our setup,  $L_t$  is the  
118 size of the nozzle throat, and the smallest dimension of the chamber determines  
119 the integral scale of the turbulent flow. Additional relevant parameters for the  
120 two experiments are given in table 1.

121 The PIV setup consists of the double-head pulsed Nd:YAG laser (120 mJ/pulse,  
122 532 nm, 15 Hz, New Wave Solo), with laser optics creating a light sheet with  
123 approximately 1 mm wide, and a  $2672 \times 4008$  pixel double exposure 12 bit CCD  
124 camera (TSI Inc. Shoreview, MN), equipped with a 100 mm Nikon macro-lens  
125 at f/2.8, resulting in a spatial resolution of  $42 \mu\text{m}/\text{pixel}$ .

126 For the PIV analysis, we used Insight 3G software (TSI Inc.) and compared  
127 it to the open source software (OpenPIV, 2019). We used a multi-pass algorithm  
128 from  $64 \times 64$  to  $32 \times 32$  pixel interrogation windows, with 50% overlap. The  
129 multi-pass method increases the dynamic range, which is especially important  
130 for the particle-laden flow cases, due to the high relative (slip) velocity. At  
131 each iteration, the outliers vectors were rejected and replaced by the mean of  
132 the five nearest neighbors. The experiments consist of 4 runs at two flow rates  
133 with/without particles. Every experimental run consists of 5 sets (repetitions),  
134 125 pairs of images each.

135 The mean flow in the region of interest is shown qualitatively in Fig. 1d  
136 as color-coded vector plot and streamlines. The spatial coordinates  $x$  and  $y$   
137 are normalized by the nozzle width  $L_t$ . Note that the position of the region  
138 of interest is shown in Fig. 1c. The bottom side is 40 mm away from the  
139 nozzle throat. The streamlines of the flow field for both Reynolds numbers are  
140 practically identical, except for the representative velocity scale at the nozzle  
141 throat of 96 m/s for the low flow rate and 135 m/s for the high flow rate  
142 experiments.

### 143 2.1. Particles

144 We used non-spherical alumina particles that are common in solid propel-  
145 lants for rocket engines and other industrial applications. An effective particle  
146 diameter  $d_p$  was measured with a laser diffraction device (Malvern Analytical)  
147 and presented in Fig. 2a. In Fig. 2b, we present the reciprocal of the inscribed  
148 circle sphericity of the particles (Wadell, 1935; Riley, 1941), the square root of  
149 the ratio of the inscribed and circumscribed circles of the particle. The particle  
150 distribution cut off below  $250 \mu\text{m}$  because the particle was separated from finer  
151 particles with a  $250 \mu\text{m}$  sieve. We sieved small batches (about 10 gram) in a  
152 controlled manner to verify fine particles were removed after sieving. The mean  
153 sphericity of 56 particles, examined under a microscope, is  $\Psi_m = 0.81 \pm 0.1$ .  
154 The microscopic images are shown in Fig. 2c, emphasizing random shapes, sharp  
155 edges, rough surfaces, cavities, and protrusions.

156 In table 1, we present the flow and particle parameters (some are given as  
157 the range of values in the chamber) for the two experiments. Using PIV data  
158 and the aforementioned definitions in Eqs. (2) – (4), we estimated the particle  
159 response time scales and the Stokes number. The residence times of the particles,  
160 estimated from  $\tau_r = H/V_p$  when  $H$  is the height of the chamber and  $V_p$  in the

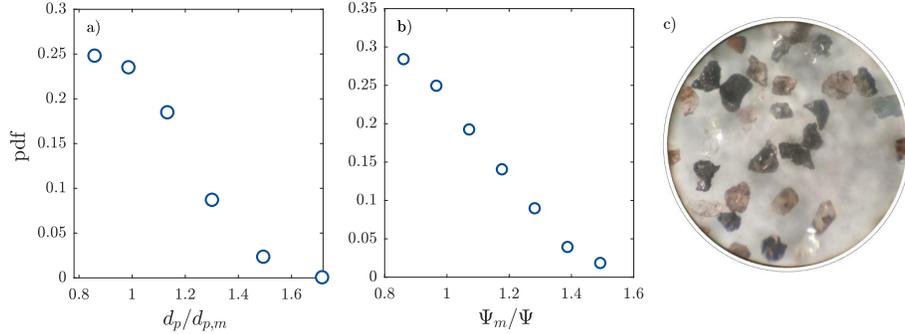


Figure 2: a) Probability density function (PDF) of particle effective diameters  $d_p$  defined as a diameter of an equivalent sphere and normalized by the effective mean diameter  $d_{p,m}$  of 320  $\mu\text{m}$  b) PDF of reciprocal of sphericity  $\Psi_m^{-1}$  normalized by the mean sphericity  $\Psi_m^{-1}$  c) alumina particle's picture under a microscope.

161 mean particle velocity, were 30 to 40 ms. The ratio of particle response time to  
 162 the residence time,  $\tau_p/\tau_r$ , is between 2 and 4, for the two Reynolds number runs.  
 163 This ratio explains that particles leave the chamber before they can respond to  
 164 the air streamwise velocity.

Furthermore, we estimate the response of the particles to the spatial acceleration of streamwise velocity using the acceleration time scale,  $\tau_a$ :

$$\tau_a = (dU_c/dx)^{-1} \quad (6)$$

165 and the ratio of scales,  $\tau_a/\tau_p$ . Mean slip due to acceleration of the flow is  
 166 expected when  $\tau_a/\tau_p > 1$ . In our flow, however,  $\tau_a/\tau_p \ll 1$  is everywhere in  
 167 the chamber (table 1). Thus, these particles can be characterized in general as  
 168 “unresponsive” (Hardalupas et al., 1989). It is also important to mention that  
 169 when  $\tau_a/\tau_p = 1$ , there is a mean slip for finite-size particles due to the shear  
 170 across the particle diameter.

171 The time scale ratios do not mean that there is insignificant local particle-  
 172 turbulence interaction. Conversely, there is a substantial transfer of momentum  
 173 between the particulate phase and the turbulent fluctuations of the carrier flow,  
 174 as will be explained in the following.

Table 1: Particle and flow parameters:  $Re_L$  based on flow rate,  $\tau_p$  is the particle response time, Eq (3),  $\tau_a$  is the flow acceleration time scale, Eq. (6),  $\tau_r$  is the particle residence time estimated from  $\tau_r = H/V_p$  when  $H$  is the height of the chamber,  $t_f$  is the integral time scale,  $t_f = L_t/U_f$ ,  $St$  is the Stokes number, Eq. (4),  $\tau_a$  is the acceleration time scale, Eq. (6), particle Reynolds number, Eq. (1),  $L$  is the integral length scale based on the autocorrelation function and  $\eta$  is the Kolmogorov length scale  $\eta = (\nu^3/\epsilon)^{1/4}$ , when  $\epsilon$  is the dissipation derived from the structure function.

Exp.	$Re_L$	$\tau_p$ (ms)	$\tau_a$ (ms)	$\tau_r$ (ms)	$t_f$ (ms)	$St$	$\tau_p/\tau_r$	$\tau_a/\tau_p$	$Re_p$	$L$ (mm)	$\eta$ ( $\mu\text{m}$ )
1	260000	75-90	0.1-1	30	9-11	85	2-3	0.0013- 0.011	300-450	9	62
2	185000	95-121	0.2-3.4	40	13-15	75	2-4	0.0021-0.028	450-650	9	76

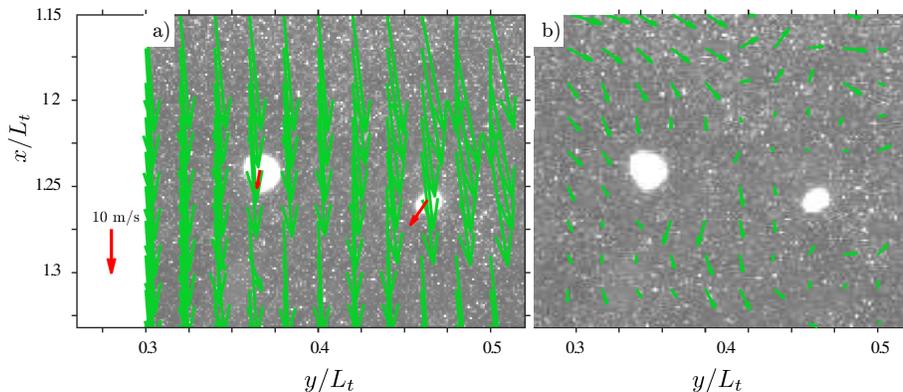


Figure 3: Instantaneous flow field of the carrier phase in the green vectors and particulate phase in the red vectors; a) for instantaneous flow field; and b) for the fluctuations, overlapped on the original PIV image. The flow field was taken from the dashed square in Fig. 1.

## 175 2.2. Two-phase PIV/PTV velocity analysis

176 We follow the procedure previously reported by Khalitov and Longmire  
 177 (2002), among others. We filter PIV images based on the size and intensity  
 178 of objects, (above 15 pixels in diameter and intensity level of 200/255) to create  
 179 particle-free PIV images from which we obtain turbulent velocity fields. The  
 180 separated images of large particles processed with particle tracking velocimetry  
 181 (PTV) analysis, using the nearest neighbor algorithm are written in Matlab  
 182 (Mathworks Inc.). In Fig. 3, we present an example of a small region in an  
 183 instantaneous flow field (green arrows overlaying the original image) of the car-  
 184 rier phase and particulate phase on the left panel, and the fluctuating flow field  
 185 in the right panel (after subtracting the ensemble averaged flow field, shown in  
 186 Fig. 1c.)

## 187 3. Results

188 In this section we will summarize the main results obtained from the two-  
 189 phase PIV/PTV measurements. We present first the definition of the local mass  
 190 loading ratio, describing the ratio of particles mass to the mass of air, varying  
 191 with the distance to the nozzle. The mass distribution is not uniform in the  
 192 flow field and this fact is reflected in the the flow field results. We proceed  
 193 to the comparison of the mean and turbulent flow profiles for unladen versus  
 194 particle-laden flows and conclude the results section with the local analysis of  
 195 particle-turbulence interactions.

### 196 3.1. Local mass loading ratio

197 The mass fraction or mass loading ratio,  $\phi$ , is defined as the ratio of particle  
 198 mass in respect to that of the fluid. We estimate the local mass loading at

199 various distances from the beginning of the measurement volume based on the  
 200 number of particles,  $N$ , extracted from PIV images, and their size distribution,  
 201 shown in Fig. 2a. The mass of particles is divided by the mass of air in the  
 202 measurement volume. This volume is calculated as the area of interest in the  
 203 PIV image times the laser sheet thickness, excluding the volume of particles  
 204 within the measurement volume. The thickness of the laser, obtained from the  
 205 reflection of the laser from a calibration target inside the measurement section.  
 206 The reflection was recorded with the high magnification PIV camera and es-  
 207 timated to be approximately 1 mm. The volume of the particles we estimate  
 208 using their equivalent diameter of  $320 \mu\text{m}$ , obtained as the weighted mean from  
 209 the probability distribution in Fig 2a. We estimate the errors due to spatial  
 210 inhomogeneity, laser sheet thickness non-uniformity, and particle size distribu-  
 211 tion approximations to sum up to 10%. The corresponding volume fractions  
 212 are  $\langle\phi_v\rangle = 3.7 - 7.4 \times 10^{-5}$  for the low flow rate and  $0.1 - 0.3 \times 10^{-5}$  for the  
 213 high flow rate, respectively. The volume loading range corresponds to the two-  
 214 way coupling regime, (Elghobashi and Trusedell, 1993), far from the four-way  
 215 coupling regime  $\langle\phi_v\rangle > 10^{-2}$ . Although recent computational studies (Esmaily  
 216 and Horwitz, 2017) have shown that even at low volume fractions there is a  
 217 possibility of inter-particle interactions, we could not find any evidence of such  
 218 interactions in the results.

219 We present the local mass loading ratio, averaged from the ensemble of PIV  
 220 images, and horizontally across the measurement volume,  $\langle\phi\rangle$ , in Fig. 4a. Note  
 221 that the streamwise flow direction is from small  $x/L_t$  to large  $x/L_t$ , and the  
 222 mass loading ratio increases as the flow with particles approaches the nozzle.  
 223 The particles trajectories converge with the flow towards the nozzle and the  
 224 mass loading increases because of the conservation of mass. The mass loading  
 225 of the particles could not be precisely controlled in the present setup, as the  
 226 particles enter the air flow from a pneumatic seeder that was kept at constant  
 227 pressure and flow rate. This experimental artifact leads to a higher particle  
 228 entrainment rate and the higher on average mass loading, mass loading for the  
 229 lower air flow case. Accordingly, a larger number of particles in the chamber  
 230 lead to a steeper mass loading increase rate as the flow accelerates towards the  
 231 nozzle.

232 It should be noted that due to the two round cavities on both sides of the  
 233 chamber from which particles rebound at high speed, few particles arriving at  
 234 a large angle to the streamwise direction were excluded from the present data.

### 235 3.2. Mean air and particle velocities

236 In Fig. 4b, we plot the variation of the average streamwise velocity along the  
 237 centerline,  $U_c$  (hereinafter capital letters denote the ensemble averaged quanti-  
 238 ties, lower case letters for turbulent quantities) for the particle unladen (filled  
 239 triangles) and laden cases (open circles) for the two Reynolds numbers (differ-  
 240 ent colors). In addition, we plot the average velocity of particles (squares). In  
 241 the lower panel, Fig. 4c-d, we present the mean velocity profiles (unladen and  
 242 laden flow cases) at several distances from the nozzle for a more quantitative

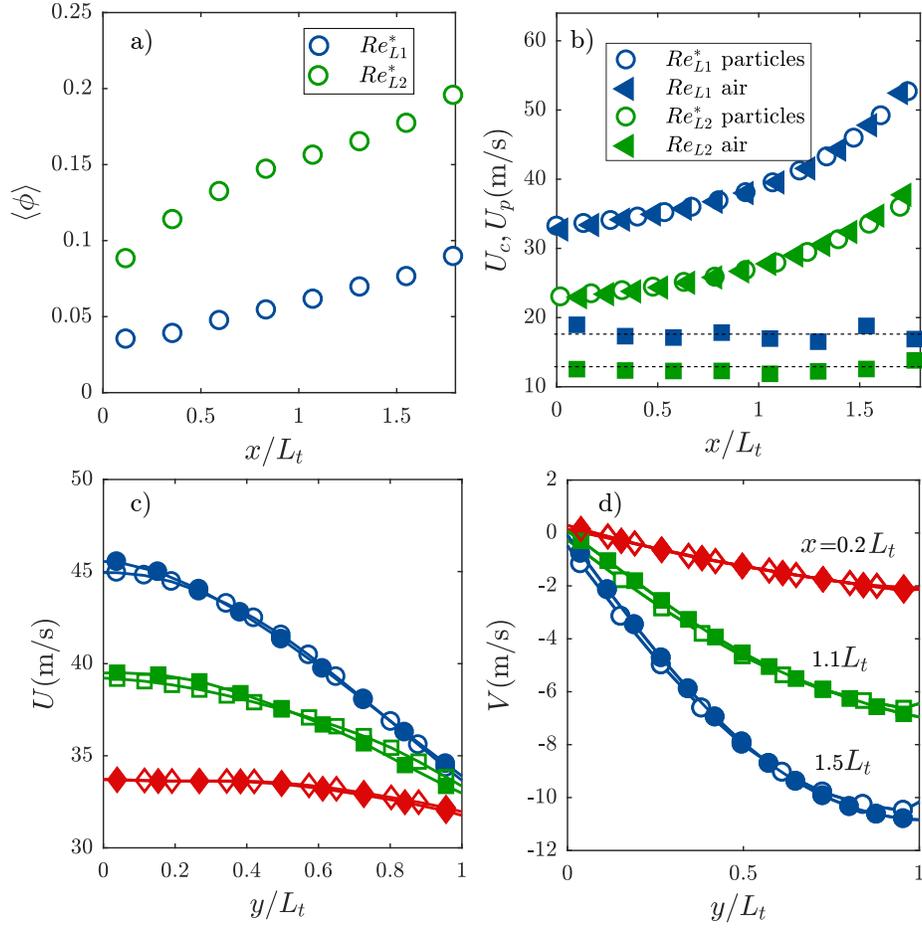


Figure 4: a) Averaged mass loading  $\langle \phi \rangle$  along the centerline. Superscript \* denotes the particle laden cases.  $x/L_t$  b) Air mean air flow velocity along the centerline of the chamber,  $U_c$  and particles average streamwise velocity  $U_p$ . Triangles are for the unladen cases, open circles for the particle laden cases (in both panels). Square markers are for the particle velocity  $U_p$ . c-d) Mean velocity profiles,  $U(y)$  and  $V(y)$ , respectively, for the un-laden (filled) and laden cases (open symbols) at  $Re_{L1}$ , at different distances from the nozzle,  $x/L_t = 0.2, 1.1, 1.5$  (diamonds, squares and circles, respectively).

243 presentation of the flow field. The summary of the key flow features visible in  
 244 Fig. 4b-d is:

- 245 • the mean streamwise velocity rapidly increases towards the nozzle (Fig. 4b-  
 246 c) with spatial acceleration values of  $\partial U/\partial x \approx 2,000 - 10,000 \text{ s}^{-1}$ ;
- 247 • The flow accelerates spatially also in the transverse direction, from the  
 248 sides of the measurement volume towards the centerline, with  $\partial U/\partial y \approx$   
 249  $500 - 3,000 \text{ s}^{-1}$  (Fig. 4d);
- 250 • average particle velocities,  $V_p$  are practically constant during the time  
 251 particles cross the measurement volume (squares at the bottom of Fig. 4b);
- 252 • the average air velocity distribution and amplitude have not changed in  
 253 particle-laden cases as compared to the unladen ones (the filled and open  
 254 symbols in Fig. 4b-d) ;
- 255 • the high Stokes/Reynolds number irregular inertial particles move signif-  
 256 icantly slower than the air flow and preserve their velocity (squares in  
 257 Fig. 4b), despite substantial flow acceleration.

258 The particles do not have enough time to respond to a spatial streamwise ve-  
 259 locity gradients, despite a strongly accelerating flow. This result is in agreement  
 260 with the experiments of Gilbert et al. (1955) and Gany et al. (1978); Caveny  
 261 and Gany (1979), where agglomerates of  $200 \div 1000 \mu\text{m}$  were found to move  
 262 slower as compared to the carrier flow everywhere in a two dimensional rocket  
 263 motor chamber.

### 264 3.2.1. Turbulent kinetic energy, Reynolds stresses and production

265 In Fig 5a-c we present the profiles of turbulent kinetic energy (TKE) com-  
 266 ponents: streamwise  $\langle u^2 \rangle$ , transverse  $\langle v^2 \rangle$  and the Reynolds stress component  
 267  $\langle uv \rangle$  for the  $Re_{L1}$  unladen flow case. We present profiles at the same distances  
 268 from the nozzle as for the mean flow profiles in Fig. 4c-d.

269 First, we observe from the spatial distributions that the fluctuations are  
 270 stronger at the sides (large  $y/L_t$ ), far from the centerline. The strong reduc-  
 271 tion of turbulent kinetic energy at the centerline is due to the acceleration.  
 272 Furthermore, the acceleration affects differently the streamwise component (de-  
 273 creasing) and the transverse component (increasing on the sides and constant at  
 274 the centerline shown by the order of the profiles from diamonds to circles (from  
 275  $0.2L_t$  to  $1.5L_t$ , respectively). We also observe that the Reynolds stress values  
 276 are large far from the centerline. At the centerline, partially due to symme-  
 277 try and partially due to acceleration, the Reynolds stresses are practically zero.  
 278 These results are in agreement with the modification of the turbulence structure  
 279 observed in converging channels, see, for instance Shah and Tachie (2008).

280 We combine the results from the ensemble averaged flow fields and the tur-  
 281 bulent properties to estimate the terms of turbulent kinetic energy production  
 282 in Fig 6a-d. We plot the profiles of turbulent production terms  $\langle uv \rangle \frac{\partial U}{\partial y}$ ,  $\langle uv \rangle \frac{\partial V}{\partial x}$ ,

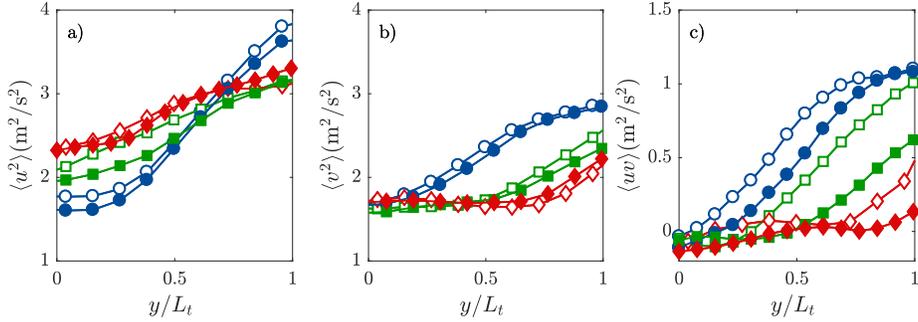


Figure 5: Turbulent kinetic energy component profiles a)  $\langle u^2 \rangle$ , b)  $\langle v^2 \rangle$  and c)  $\langle uv \rangle$ , respectively, for  $Re_{L1}$  and the un-laden case (filled symbols) and laden case (empty symbols). The symbols and colors legend are the same as in Fig. 4.

283  $\langle u^2 \rangle \frac{\partial U}{\partial x}$ , and  $\langle v^2 \rangle \frac{\partial V}{\partial y}$ , for the unladen and laden cases (filled and open symbols,  
 284 respectively) at  $Re_{L1}$  (at the same distances from the nozzle as in Fig 5).

285 The effects of acceleration on the TKE production Fig 6a-d are visible in  
 286 the terms  $\langle uv \rangle \frac{\partial U}{\partial y}$  and  $\langle uv \rangle \frac{\partial V}{\partial x}$ . The terms contribute positively to the TKE  
 287 production far from the centerline with the peak at about  $x/L_t \approx 0.5$ , and  
 288 decrease towards the centerline. This is partially due to symmetry of the flow  
 289 and diminishing derivatives  $\partial U/\partial y$  and partially due to the decorrelation of  
 290 the velocity components. Along the centerline ( $y = 0$ ), the intense spatial  
 291 acceleration towards the nozzle and TKE components  $u^2$  and  $v^2$  contribute to  
 292 a sort of “negative TKE production”. It is noteworthy that the two terms  
 293  $\langle u^2 \rangle \frac{\partial U}{\partial x}$  and  $\langle v^2 \rangle \frac{\partial V}{\partial y}$  in Fig 6c-d are also stronger as compared to the production  
 294 terms stemming from the Reynolds stresses in Fig 6a-b. On the overall, it  
 295 can be summarized that the strong spatial acceleration in the streamwise and  
 296 transverse directions due to the convergent type of the flow diminishes TKE  
 297 production terms, therefore the turbulent fluctuations in the unladen flow case  
 298 decrease towards the nozzle.

### 299 3.3. Particle-turbulence interaction mechanism

300 Figures 4b-d, 5a-c, and 6a-d present the effects of particles on the mean  
 301 flow, TKE components and the TKE production terms, respectively. We noted  
 302 that the mean flow in the chamber has unchanged insignificantly and the small  
 303 variations of a few percents appear closer to the nozzle. The centerline velocity  
 304 profiles along  $x$  and the transverse profile (e.g.,  $U(y)$ ) all show that the flow  
 305 velocity field is practically unchanged at the same locations with only a slight  
 306 reduction of the mean velocity in the particle-laden case (the results for the  
 307 lower Reynolds case are similar and not shown here for the sake of brevity). We  
 308 observe somewhat increasing fluctuating components in Fig. 5a-b, however, the  
 309 most prominent change is in the field of Reynolds stresses in Fig. 5c. Clearly, this  
 310 increase also affects the production terms shown in Fig. 6a-b. However, because  
 311 of the strong acceleration, the negative TKE production terms are dominant  
 312 and increase towards the nozzle entrance.

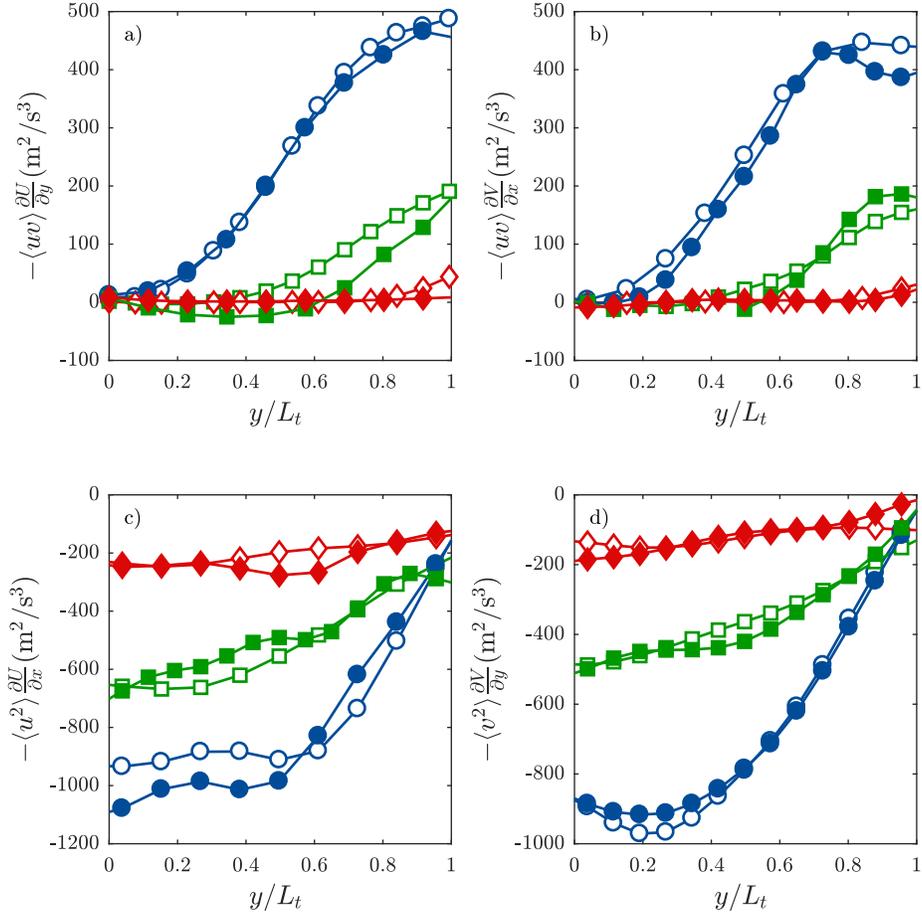


Figure 6: Profiles of turbulent production terms: a)  $\langle uv \rangle \frac{\partial U}{\partial y}$ , b)  $\langle uv \rangle \frac{\partial V}{\partial x}$ , c)  $\langle u^2 \rangle \frac{\partial U}{\partial x}$ , and d)  $\langle v^2 \rangle \frac{\partial V}{\partial y}$ , respectively, for the un-laden case (filled symbols) and laden case (empty symbols) and for  $Re_{L1}$ , at different distances from the nozzle. The symbols and colors legend is the same as in Fig. 4.

313 We also recall that the flow is in the dilute two-way coupling regime, with  
314 a relatively small number of heavy particles. Therefore, in the following we  
315 present a more insightful, local analysis around the particles and as a function  
316 of distance from the particles.

317 To reveal the local effects of particles on the turbulent flow, we use condi-  
318 tional sampling in the following form: we divide the instantaneous PIV/PTV  
319 fields in the particle-laden cases, along the centerline, into small control volumes  
320 of  $20 \times 20$  mm. From each sub-volume, we conditionally sample the turbulent  
321 fluctuations depending on whether the sub-volume in a given flow realization  
322 contains particle(s) and marked it as a region B (particles) or C (no particles)  
323 (as schematically marked in Fig. 1c). For the sake of reference we compare with  
324 the distributions of properties in case A that is the clear air flow case at the  
325 same Reynolds number and at the same sub-volume locations.

326 In Fig. 7, we present a comparison of probability distribution functions  
327 (PDF) of the streamwise fluctuations in the case of a unladen flow case (red  
328 triangles) with these at two conditional samples: the regions with at least one  
329 particle (B) and the regions in the particle-laden case that do not contain inertial  
330 particles (C). Both PDFs of the particle-laden cases have wider tails, cor-  
331 responding to higher  $u'$  values (up to 3 times higher values, as seen in Fig. 7b.)  
332 The turbulent flow in the proximity of the inertial particles (case B) is sig-  
333 nificantly different from the unladen case (case A). It is noteworthy that the  
334 turbulent fluctuations are stronger also far from the particles (case C), as if the  
335 flow is “contaminated” with the velocity fluctuations stemming from the local  
336 particle-turbulence interactions. The result are a different view on the increase  
337 of fluctuations in particle-laden case, shown above in Fig. 5.

338 Reflecting on the introductory section, we can attribute these local effects  
339 with negative fluctuations to the “vortex shedding” regime and infer that the  
340 wakes are transported and affect the flow for a substantially longer time scale as  
341 compared to the particle residence time. To quantify the region of influence of  
342 particles on turbulent fluctuations, we present in Fig. 7b the r.m.s of streamwise  
343 fluctuations (denoted by  $u'$ ) in particle-laden cases normalized by the value of  
344 the unladen cases for the two Reynolds numbers. For this plot, we sample PIV  
345 flow realizations in respect to the particle centroids in the streamwise direction  
346 (i.e., in the Lagrangian frame of reference attached to the particle center). The  
347 normalized r.m.s. of streamwise fluctuations in the particle wake is plotted  
348 versus the streamwise distance from the particle, normalized by the particle  
349 average diameter,  $d_p$  (downstream, in the direction of motion of the particle).  
350 We observe significantly higher turbulent fluctuation within a region of at least  
351 5 diameters and the effect of slightly increased turbulent fluctuations far from  
352 the particle, supporting the aforementioned results in terms of distributions in  
353 Fig. 7a or profiles in Fig. 5a-c.

354 We are also interested in the local analysis of the effect of decorrelation on  
355 the streamwise and transverse fluctuations observed in Fig. 5c. The results of  
356 the conditional sampling analysis along the centerline are shown in Fig. 8. We  
357 present the values of  $u'$  and  $v'$  of the local/non-local conditional samples and  
358 of the unladen case together to emphasize the different rate of decrease of the

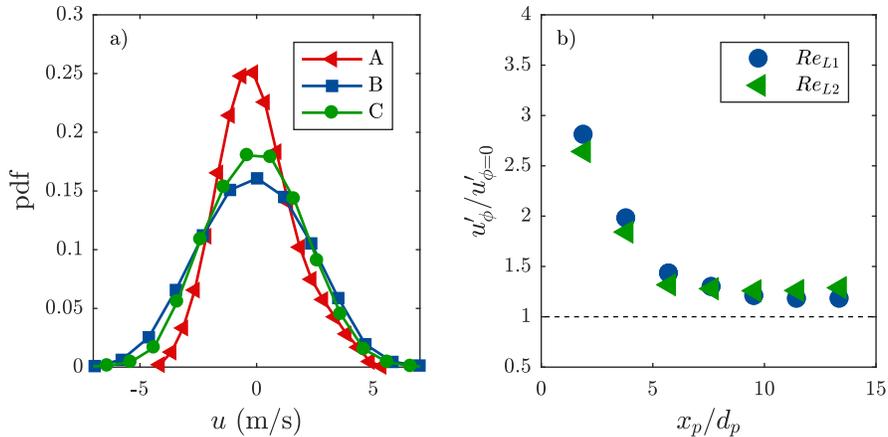


Figure 7: a) PDF of streamwise velocity fluctuations at  $x/L_t \approx 1$  along the centerline,  $y = 0$ , where the red triangles denote the unladen case (A), blue squares denote the particle-laden flow with instantaneous accumulation of particles (B) and the green circles denote the particle-laden flow with locally clear air (C). Skewness values are 0.25, -0.11 and 0.48, respectively. b) Root-mean-square of streamwise fluctuations  $u'$  for the particle laden cases at two Reynolds numbers as a function of distance from the particle, normalized by the corresponding r.m.s. of the unladen flow case. The distance is measured along streamwise direction from the origin attached to the particle,  $x_p$ , normalized by the mean particle diameter.

359 fluctuations in the direction of mean flow acceleration. The ratio of r.m.s. of the  
 360 fluctuations  $v'/u'$  which is in some sense a measure of anisotropy (a horizontal  
 361 line at  $v'/u' = 1$  means the isotropic ratio of fluctuations) is shown in Fig. 8b.

362 The local analysis reveals very peculiar phenomena arising due to the competi-  
 363 tion between the effect of strong acceleration (namely, a strong decrease of  
 364 streamwise fluctuations and an increase of spanwise fluctuations), and the effect  
 365 of the particles, which increase the fluctuations locally in the downstream wake  
 366 of the particle. The peculiarity is that the two counteracting effects lead to an  
 367 isotropic ratio of turbulent fluctuations. We recall that the effects are linked to  
 368 the local mass fraction increasing towards the nozzle, as was shown in Fig. 4a.

#### 369 4. Summary and conclusions

370 In this work, we created the experimental setup of a two dimensional model  
 371 of a rocket engine and studied the particle-turbulence interaction when the  
 372 particulate phase consists of dispersed alumina particles of irregular shape in  
 373 the size range of  $250 - 550 \mu\text{m}$ . We focused on the pre-nozzle region in which  
 374 the carrier phase flow spatially accelerates towards the nozzle. We applied a  
 375 two-phase PIV/PTV algorithm and quantified the carrier and particulate phase  
 376 velocity fields.

377 The alumina irregularly shaped particles are strongly inertial with relatively  
 378 high Stokes and particle Reynolds numbers. The particles pass the finite size

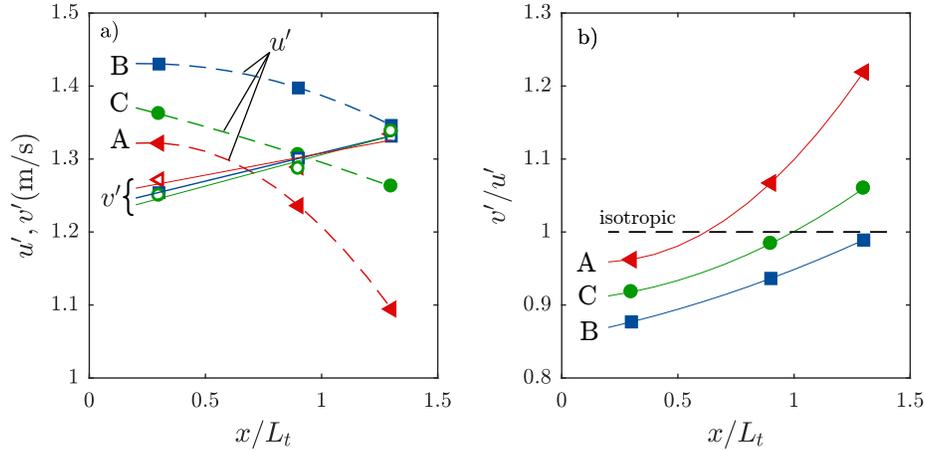


Figure 8: a) Root-mean-square of fluctuation components,  $v'$  and  $u'$  along the centerline  $x/L_t$  (same legend as in Fig. 7). Filled markers denote  $u'$  and open markers are for  $v'$ . b) anisotropy measure,  $v'/u'$  for the three cases A-C, a horizontal line at  $v'/u' = 1$  emphasizes the isotropic ratio.

379 flow chamber quickly, as compared to their response time scale. As a conse-  
 380 quence, the interactions are abrupt and strong, but the residence time is much  
 381 shorter as compared to the particle response time. Therefore, in this peculiar  
 382 situation, the particles move at almost constant average velocity, despite the  
 383 fact that the carrier phase flow rapidly accelerates towards the nozzle. This  
 384 leads to the high and monotonically increasing relative (slip) velocity between  
 385 the particulate phase and carrier flow.

386 The combination of the high particle-fluid relative velocity, slow response  
 387 time, and rapid acceleration of the air mean flow leads to substantial turbu-  
 388 lence argumentation, mostly in the streamwise component. The particle-related  
 389 mechanism for these Stokes numbers range from  $St > 75$  and the particle  
 390 Reynolds numbers  $Re_p > 300$  were termed in the literature as “vortex shedding”  
 391 mechanism Hetsroni (1989); Balachndar and Eaton (2010). In the present case,  
 392 in particular, the particles move slower than the carrier fluid flow. Thus, a tur-  
 393 bulent wake, a region where the flow slows down, is in the direction of relative  
 394 velocity, which defined as  $\vec{V}_r = \vec{U}_f - \vec{V}_p$ . The wake region “downstream” in  
 395 respect to the particle. It means that the next particle position will be inside  
 396 the wake of the particle itself at the previous time instant. More detailed local  
 397 flow around the particles analysis shows that on average, a local reduction of  
 398 the air flow velocity in the particle wake is pronounced up to five particle diam-  
 399 eters downstream from the particle. We presented the comparison of the local  
 400 turbulence augmentation in the proximity of the particles and compared it to  
 401 the turbulence augmentation in the entire region of interest. We also demon-  
 402 strated the peculiar situation of streamline convergence leading to an increase of  
 403 the local mass fraction, streamwise acceleration, and particle-turbulence inter-  
 404 actions. First, the streamwise average velocity acceleration significantly reduces

405 the streamwise turbulent fluctuations. Second, inertial particles of irregular  
406 shape create streamwise fluctuations in their wakes due to the vortex shed-  
407 ding and compensate the mean flow acceleration effect. In addition to the dra-  
408 matic increase of TKE, the particle wakes are unexpectedly more isotropic than  
409 the surrounding turbulence. Furthermore, the particle wakes are much more  
410 isotropic as compared to the unladen flow case with the mean flow acceleration.

411 In our experiment, the particle mass fraction is monotonically increasing  
412 towards the nozzle due to mass conservation and streamlines convergence (see  
413 4). Nevertheless, in the measurement region of interest, the mass fraction is in  
414 the two-way coupling regime and we did not observe any clustering of particles.  
415 Our conclusions are therefore, limited to the dilute two-way coupling regime.

416 In respect to the aforementioned particle-flow dimensionless parameters, we  
417 have estimated that  $P_a > 10^5$  in the entire measurement region. As suggested  
418 by Tanaka and Eaton (2008), it falls in the range that predicts an increase in  
419 turbulence. The length scales ratio,  $d_p/L$  (Gore and Crowe, 1989) is lower than  
420 0.1 and predicts attenuation, however our particles lead to augmentation. This  
421 discrepancy is likely to reflect the fact that the main effect is due to the particle  
422 wakes that are five times larger than the particle effective diameter.

423 This empirical work does not improve significantly our ability to predict the  
424 effects of particle-turbulence interactions in a general case, because it is lim-  
425 ited to two Reynolds number cases, the finite range of mass loading and the  
426 specific type of particles studied. However, it adds a few important observa-  
427 tions relevant for the case of particle-laden flows with high Stokes/Reynolds  
428 numbers irregularly shaped particles, especially in the case of accelerating and  
429 converging incompressible flows. We demonstrate the mechanism by which a  
430 small mass fraction of particles in the accelerating and converging flow leads to  
431 up to 20% increase of turbulent kinetic energy (at  $x/L_t = 1.3$  in Fig. 8.a)). It  
432 could lead to a comprehensive choice of the particle shape and density ( $St, Re_p$ )  
433 and the mass fraction (number of particles per volume of solid propellant) that  
434 can compensate the decrease of TKE by the flow acceleration. Furthermore,  
435 we demonstrate that irregularly shaped particles, moving more slowly than the  
436 surrounding fluid, will create streamwise fluctuations that lead to isotropic tur-  
437 bulence regions with important consequences for mixing and transport flux.  
438 We can infer that both the turbulent mixing and combustion rates could be  
439 enhanced using these mechanisms. The right choice of turbulence enhancing  
440 particles with the focus on the near-nozzle region shall affect the overall perfor-  
441 mance of the rocket engine and modify its exhaust content. The two-way global  
442 and local coupling mechanisms could not be neglected in numerical simulations  
443 and analytical models of multi-phase rocket engines.

## 444 References

- 445 S. Balachndar, J. K. Eaton, Turbulent dispersed multiphase flow, *Annu. Rev.*  
446 *Fluid Mech.* 42 (2010) 111–133.

- 447 J. D. Kulick, J. R. Fessler, J. K. Eaton, Particle response and turbulent modi-  
448 fication in fully developed channel flow, *J. Fluid Mech.* 277 (1994) 109–134.
- 449 J. Kussin, M. Sommerfeld, Experimental studies on particle behaviour and tur-  
450 bulence modification in horizontal channel flow with different wall roughness,  
451 *Exp. Fluids* 33 (2002) 143–159.
- 452 K. T. Kiger, C. Pan, Suspension and turbulence modification effects of solid  
453 particulates on a horizontal turbulent channel flow, *J. Turb.* 3 (2002) 1–21.
- 454 J. Li, H. Wang, Z. Li, S. Chen, C. Zheng, An experimental study on turbulence  
455 modifiction in near-wall boundary layer of dilure gas-particle channel flow,  
456 *Exp. Fulids* 53 (2012) 1385– 1403.
- 457 M. Cisse, H. Homann, J. Bec, Slipping motion of large neutrally buoyant par-  
458 ticles in turbulence, *J. Fluid Mech.* 735 (2013).
- 459 G. Hetsroni, Particles turbulence interactions, *J. Multiph. Flow* 15 (1989)  
460 341–351.
- 461 T. Tanaka, J. K. Eaton, Classification of turbulence modification by dispersed  
462 spheres using novel dimensionless number, *Phys. Rev. Lett.* 101 (2008) 297–  
463 285.
- 464 Y. Meller, A. Liberzon, Particle–fluid interaction forces as the source of accel-  
465 eration PDF invariance in particle size, *Int. J. Multiph. Flow* 76 (2015) 22 –  
466 31.
- 467 C. T. Crowe, J. D. Schwarzkopf, M. Sommerfeld, Y. Tsuji, *Multiphase Flows*  
468 *with Droplets and Particles*, CRC Press, 2011.
- 469 R. A. Gore, C. T. Crowe, Effect of particle size on modulating turbulent inten-  
470 sity, *Int. J Multiph. Flow* 15 (1989) 279–285.
- 471 A. Gany, L. Caveny, M. Summerfield, Aluminized solid propellants burning in  
472 a rocket motor flow field, *AIAA* 16 (1978) 736–739.
- 473 L. H. Caveny, A. Gany, Breakup of Al/Al<sub>2</sub>O<sub>3</sub> agglomerates in accelerating  
474 flowfields, *AIAA* 17 (1979) 1368–1371.
- 475 F. Prevost, J. Boree, H. J. Nuglisch, G. Charnay, Measurements of fluid/particle  
476 correlated motion in the far field of an axisymmetric jet, *Int. J. Multiph. Flow*  
477 22 (1996) 685–701.
- 478 M. Elhimer, O. Praud, M. Marchal, C. Cazin, R. Bazile, Simultaneous  
479 PIV/PTV velocimetry technique in a turbulent particle-laden flow, *J. Vi-*  
480 *sual.* 20 (2017) 289–304.
- 481 C. Poelma, J. Westerweel, G. Ooms, Turbulence statistic from optical whole-  
482 field measurements in particle-laden turbulence, *Exp. Fluids* 40 (2006) 347–  
483 363.

- 484 D. A. Khalitov, K. Longmire, Simultaneous two-phase PIV by two-parameter  
485 phase discrimination, *Exp. Fluids* 32 (2002) 252–268.
- 486 W. Hwang, J. K. Eaton, Homogeneous and isotropic turbulence modulation by  
487 small heavy ( $St \approx 50$ ) particles, *J. Fluid Mech.* 564 (2006) 361–393.
- 488 K. N. Volkov, V. N. Emel’yanov, I. V. Kurovs, Flow and motion of condensed-  
489 phase particles in the prenozzle space on solid-propellant rocket motors, *J.*  
490 *Eng. Phys. Thermophys.* 85 (2012) 724–731.
- 491 A. Ciucci, G. Iaccarino, Numerical analysis of the turbulent flow and alumina  
492 particles in solid rocket motors, *J. Eng. Phys. Thermophys.* 85 (2012) 1–15.
- 493 OpenPIV, OpenPIV/OpenPIV-Python, 2019. URL:  
494 <https://doi.org/10.5281/zenodo.3566451>. doi:10.5281/zenodo.3566451.
- 495 H. Wadell, Volume, shape and roundness of rock particles, *J. Geology* 40 (1935)  
496 443–451.
- 497 N. A. Riley, Projection sphericity, *J. Sediment. Petrology* 11 (1941) 94–97.
- 498 Y. Hardalupas, A. M. K. P. Taylor, J. H. Whitelaw, Velocity and particle-flux  
499 characteristics of turbulent particle-laden jets, *Proc. Royal Soc. A.* 426 (1989)  
500 31–78.
- 501 S. Elghobashi, G. C. Trusedell, On the two-way interaction between homoge-  
502 neous turbulence and dispersed solid particles. I: Turbulence modification,  
503 *Phys. Fluids* 5 (1993) 177–216.
- 504 M. Esmaily, J. Horwitz, Investigation of a four-way coupling regime using a  
505 corrected point-particle approach, *Annual Research Brief* (2017) 49–62.
- 506 M. Gilbert, L. Davis, D. Altman, Velocity lag of particles in linearly accelerated  
507 combustion gases, *J. Jet Prop.* 25 (1955) 26–30.
- 508 M. Shah, M. Tachie, PIV study of turbulent flow in asymmetric converging and  
509 diverging channels, *Trans. ASME, Journal of Fluids Engineering* 130 (2008)  
510 011204–1.