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Turbulence modification of a particle-laden flow in a rocket motor model

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1. Abstract

In particle-laden flows the turbulent kinetic energy (TKE) can either increase or decrease in presence of dispersed particle phase. Accurate estimate of magnitude of TKE at different flow regions is important for the design and performance of a rocket motor. Particle-laden turbulent flows were investigated in a two-dimensional model of a rocket engine cross-section, using Particle Image Velocimetry (PIV). The high mass loading (up to 120) of dispersed inertial alumina particles ($St \approx 10^4$) leads to two-way coupling flow regime at different flow regions. The results showed that with increasing of mass loading the TKE was increasing accordingly.

Keywords: Rocket motor, Particle-laden flow, Turbulence modification, Particle image velocimetry

2. Introduction

Particle-laden turbulent flows are ubiquitously present in nature and industrial applications. In this study we are interested in the problem of dispersed alumina particles (350 μm) moving in a turbulent flow through a model of a rocket motor. The problem is relevant for case where solid particles are added to the high temperature flow in order to improve and control the combustion [1]. High mass loading of the particles leads to the two-way coupling regime and possibly the four-way coupling regime in some flow regions of the motor. Understanding of the turbulent flow along with particle-flow and particle-particle interactions in the rocket motor has an impact on the design and performance of the motor.

Previous studies have shown that dispersion of particles can either increase ([2], [3], [4]) or decrease ([5], [6], [7]) turbulent kinetic energy (TKE) and the dissipation. Gore and Crowe [8] proposed that the ratio of the particle diameter to the large length scale , d_p/L, defines whether the turbulence fluctuations will increase or decrease. Tanaka and Eaton [9], extended this work by proposing the momentum parameter $Pa=Re^2St(\eta/L)^3$ that includes also dependency on particle density.

The physics of turbulence modification by particles is not completely understood in isotropic turbulence, and it becomes more complex in a rocket motor chamber where flow and particles accelerate into and through the nozzle and due to the chamber complex geometry. Our aim is to study experimentally the particle-laden turbulent flow in a simplified model of a rocket motor. The measurements could hopefully assist development of a model of turbulence modification that can be incorporated in computational fluid dynamics simulations.

3. Experimental methods

The setup consists of 1/10 reduced model of a cross-section of a rocket engine, see figure 1. The flow is assumed to be two-dimensional inside a chamber which has the width of 35 mm, maximum length of 245 mm and the nozzle throat is 35 mm. A blower pumps air through the model at flow rate up to 0.2 m^3/s. The flow is seeded simultaneously with olive oil tracers particles (1 µm) via Laskin nozzle and inertial alumina particles. A double-head Nd:YAG laser (120 mJ/pulse, New Wave Solo) illuminated the flow, imaged by 11 Mp CCD camera (TSI Inc). Time separation between two PIV images was 10 µs. The continuous phase velocities were analyzed by Particle image Velocimetry (PIV) with Insight3G (TSI Inc) and the dispersed phase with Particle Tracking Velocimetry (PTV).

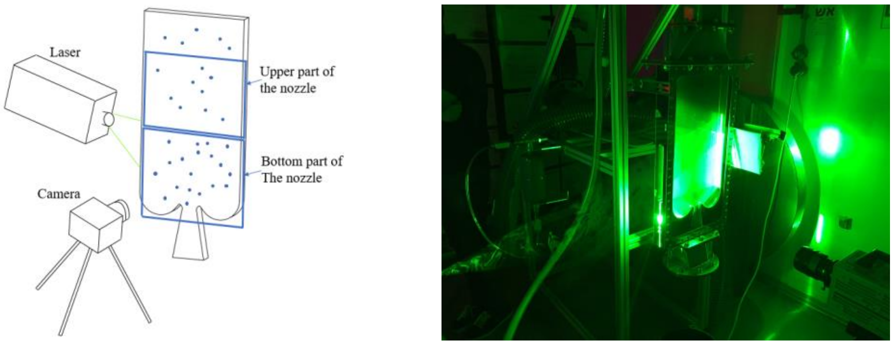

Figure 1- (left) Schematic sketch of the system, defining two measurement regions. (right) Photo of the system during the PIV/PTV experiment.

In order to calculate the particle mass loading and to obtain PTV analysis we need to separate the alumina particle images from tracer images, similar to the two-phase PIV/PTV studies in Ref. [10,11]. For this purpose we use the differences in objects size and intensity. Binarization of the images with intensity threshold and elimination of particles with size less than a predefined size (e.g. 14 pixels in this magnification) produced images shown in figure 2, emphasizing the raw image before and after the image prepossessing. Particle images created by the 90-degree laser light scattering that prevents quantitative measurements of the size of each particle. Therefore, we approximate the local mass loading using the area of the pixels covered by the particles and an average particle size, obtained by optical microscope measurements.

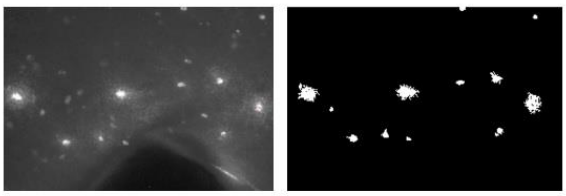

Figure 2- Images before (left) and after (right) image pre-possessing used to segment tracers from alumina particles.

4. Results

From the two-phase analysis, we get that the particle mass loading (ϕ) is increasing along the centerline of the nozzle, shown in figure 3, where y/L_t is the vertical distance from the nozzle, normalized by the nozzle throat. The origin (y=0) is at the entrance to the nozzle. Note that an apparentl plateau in ϕ that is present for small distances, $\frac{y}{L_t} \leq 0.5$ is most likely the result of the image saturation due to the reflections from a nozzle walls. Near the nozzle entrance, we predict from mass conservation that ϕ continue to grow until the throat.

From the PIV measurements, we get the velocities of the air flow surrounding alumina particles. The mean velocity magnitude of the flow is the same for the un-laden and particle-laden cases. On contrary, u_{rms} is increasing with the increasing of the mass loading resulting in even stronger increase of turbulent intensity (TI).

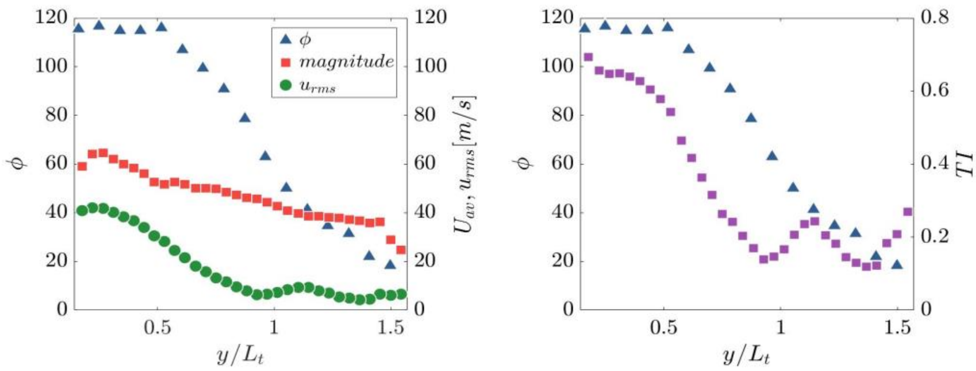

Figure 3: Turbulent velocity fluctuations, u_{rms} , mean velocity magnitude, U, and turbulent intensity profiles as a function of distance from the nozzle, along with the mass loading ϕ .

5. Conclusions

The interaction of high Reynolds number turbulent flow in a model of a rocket chamber with high mass loading of inertial alumina particles results an increase in turbulence intensity. The mean flow is not affected by the particles in this case for high mass loading of the particles. We observe that particles transfer their energy to the flow that increases velocity fluctuations and TKE. In addition, these high Stokes particles generate wakes that increase turbulent fluctuations. Our finding are in agreement with Tanaka and Eaton [9] in the sense that the results show Pa>10^5 which was categorized as a turbulence with increased TKE. This study is only a first step towards a more elaborated research focusing on the two-way coupling of particles with a turbulent flow.

6. References

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