Sub Topic: Particle Diagnostics

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Characterization of Dust Particle Flow Field in Minimum Ignition Energy Testing Apparatus Using High-Speed Digital In-Line Holography

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Abstract: Broadening the current understanding of the minimum ignition energy (MIE) concept as applied to dust explosions is critical to improving industry safety standards. Characterization of dust dispersion flow properties in a Kühner MIKE 3 MIE apparatus represents a new area of study. In this work, high-speed digital in-line holography (DIH) is employed to obtain quantitative flow field data from suspended glass particles in the ignition volume of interest. A high-speed DIH experimental study in MIE apparatus for the extraction of particle location, velocity, and size data is presented. Quantitative visual and statistical characterization of the dust particle flow field is achieved through processed holograms and their corresponding size and velocity distributions. These results demonstrate the feasibility of dust particle flow field characterization via DIH, albeit at suitably low dust concentrations. Strategies addressing the higher particle velocities and concentrations present at typical ignition times will be implemented to characterize dust dispersions in future MIE test conditions.

Keywords: Digital In-Line Holography, Minimum Ignition Energy, Particle Diagnostics

1. Introduction

Evaluation of the hazards presented by combustible dusts is critical to risk assessment and mitigation in industries that are susceptible to accidental dust explosions. Standard methods [1,2] have been adopted and developed to assess the two major components of explosion risk, namely explosion probability and severity [3]. The minimum ignition energy (MIE), the lowest energy required to ignite a combustible mixture with a capacitive spark discharge, assesses the probability of dust explosions during processing and handling [1]. The MIE is an important indicator of a relative ignition sensitivity of a particular dust, though it has been demonstrated that dust clouds are not as simply characterized by the MIE as combustible gas mixtures [4,5]. Dust cloud

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ignitibility has been shown to be strongly influenced by features of the spark circuit, such as its series resistance [6]. Shock waves from sufficiently short sparks were also shown to prohibit ignition by removing combustible material from the ignition zone, thus affecting the measured MIE [7]. Given the MIE concept's importance as an explosion risk assessment parameter, continued investigation of its application to dust explosions is merited.

Characterization of the dust particle flow field in a Kühner MIKE 3 MIE apparatus has been identified as a research area lacking detailed study and a first step towards correlating dust-specific flow properties with the MIE. High-speed digital in-line holography (DIH) [8], a laser-based volumetric imaging technique, provides particle flow field diagnostic capability to conduct studies of this nature. DIH uses coherent light to create interference patterns that are recorded using a digital image sensor [9]. Software then locates real features within the recorded holograms via numerical refocusing. DIH has been successfully used to detect, track, and size particles in a wide variety of flows [10–12]. While charge-coupled-device (CCD) cameras are often used to collect holographic particle images due to their high spatial resolution and low noise characteristics, the increased availability of higher quality complementary metal–oxide–semiconductor (CMOS) cameras, capable of capturing images at higher rates, has enabled holography experiments investigating transient particle flow-field dynamics [13]. Thus, DIH systems incorporating modern CMOS cameras leverage a simple optical setup and high frame rate imaging.

In this work, high-speed DIH diagnostics in MIE experimental system for the imaging of dusts dispersed in air and the extraction of quantitative dust particle flow field data is presented. The experimental apparatus and data processing scheme are described in Section 2. The experimental results obtained from this experiment are reported and discussed in Section 3. The major conclusions of this work are finally presented in Section 4.

2. Methods

The experimental apparatus used to produce dust particle holograms is illustrated schematically in Fig. 1. The high-speed DIH and MIE apparatus comprises three component sections. The laser component produces a collimated laser beam that illuminates the dust dispersion generated by the MIE apparatus, while the imaging and data acquisition component records holograms at high speed and stores them for subsequent data processing.

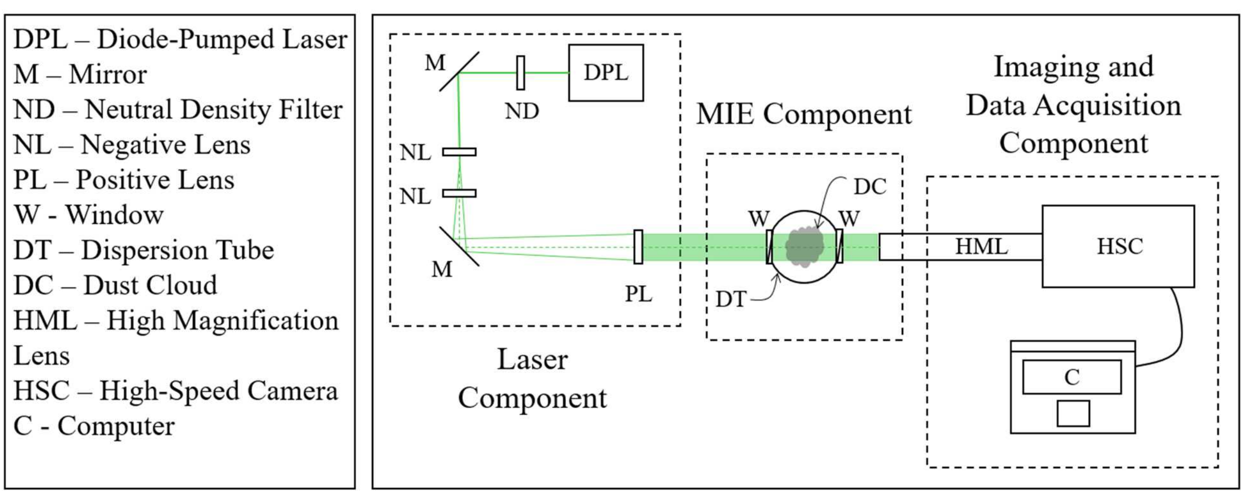


Fig. 1: Schematic for the high-speed DIH and MIE experimental apparatus.

Illumination originating in the laser component is produced by a diode-pumped solid state (DPSS) laser (Oxxius 532 nm, continuous-wave). The laser beam is attenuated using neutral density filters, expanded, and collimated such that the resulting beam is appropriately sized and at an intensity that prevents oversaturation of the camera sensor. The diameter of the collomated beam is approximately 50 mm.

The collimated beam is passed through the MIE component, which comprises a modified MIE apparatus (Kühner MIKE 3). The 1.2 L glass tube present in the standard MIE testing configuration is replaced by a polycarbonate tube of the same dimensions. This new tube is fitted with windows perpendicular to the axis of the laser beam such that the collimated beam may pass through the tube without being distorted. The functional electrodes present in the standard configuration are also removed for these initial experiments. The modified tube satisfies the DIH system's optical requirements and allows for the characterization of the dust particle flow field without the obstruction imposed by the electrodes during these initial tests. The remaining features of the MIE apparatus are unchanged from its standard configuration. A dust dispersion is generated via compressed air (7 bar) that is directed upwards into the tube by a mushroom-shaped nozzle. A stainless-steel flapper prevents the dust dispersion from entering the environment and damaging the imaging system. The dust dispersion considered for this experiment is composed of glass beads (900 mg, d ≤ 106 μm) at a nominal dust concentration of 750 g/m^3. This concentration is relative to the mass of dust and the total volume of the dispersion tube.

The interference between the collimated laser beam and the light scattered off of dust particles in the tube is received by the imaging and data acquisition system. A long-distance microscope lens (Infinity K2 DistaMax, CF-4 objective) is used to achieve appropriate magnification levels, and holograms are recorded with a CMOS camera (Photron FASTCAM SA-Z). A calibration image of a 1951 USAF resolution test chart is captured and analyzed to quantify the magnification of the imaging system. For this experiment a magnification of 225 pixels/mm is determined. For this experiment, the front focal plane of the imaging system is located at the center of the dispersion tube. The camera is manually triggered and timed so that as much of the dispersion can be captured at the desired camera settings. The experimental apparatus is shown photographically in Fig. 2 for clarity.

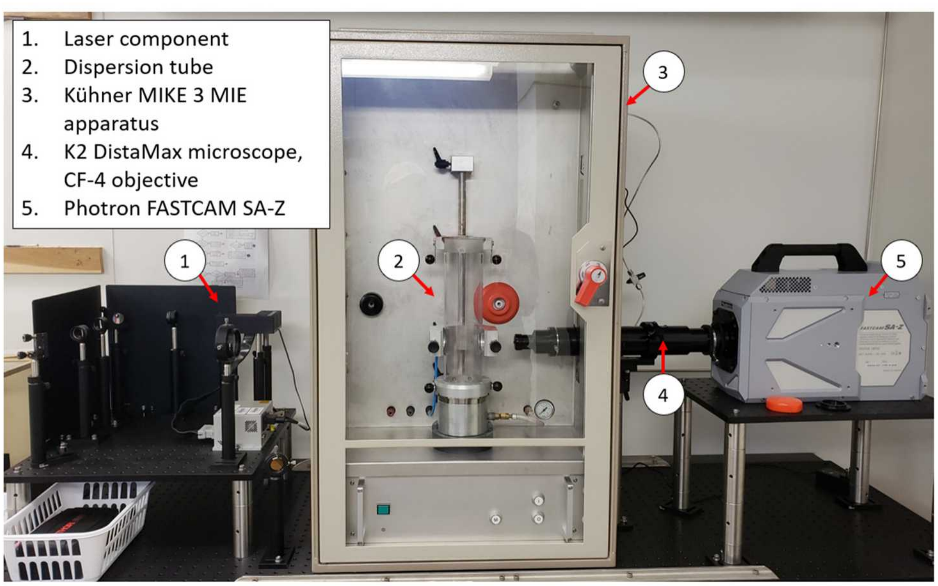
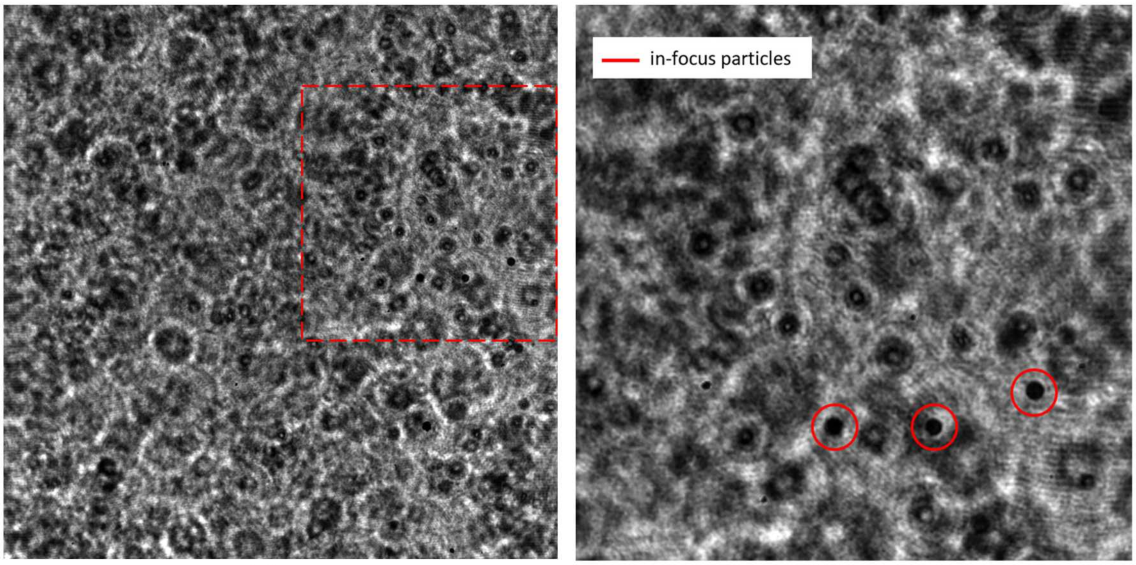


Fig. 2: Experimental apparatus configured for high-speed DIH of dust dispersions.

After the dispersion, the recorded holograms are stored and later transferred to a separate workstation for processing. A sample unprocessed hologram acquired from the imaging system is shown in Fig. 3(a). As seen in Fig. 3(b), particles located at the front focal plane of the imaging system appear in focus while out-of-plane particles display the diffraction patterns characteristic of holographic methods.



(a) (b)

Fig. 3: (a) Unprocessed hologram of xx mm × xx mm, and (b) zoomed in region of yy mm × xx mm showing in-focus particles.

Data processing is conducted on a dedicated workstation with a code that process a selected sequence of holograms image by image. Particles are identified and tracked using the methods described in Guildenbecher et al. [14] and Gao et al. [15]. The holography processing routine returns a corresponding sequence of overlaid images that display all detected particles in focus and with an in-plane velocity vector. The detected particles are given colored outlines to signify variation in particle sizes. The processing routine also produces histograms showing the distribution of particle sizes and in-plane velocity components over the selected hologram sequence. This experiment omits data produced for the out-of-plane positions and velocities of the detected particles due to high uncertainty. The source of this uncertainty, namely the depth-of focus-problem is discussed elsewhere [9].

3. Results and Discussion

A representative overlaid image from the processed hologram sequence, showing the dust particle flow field approximately 1.12 seconds after the dispersion enters the field of view, can be seen in Fig. 4. This dispersion time was selected such that the concentration of particles within the field of view was low enough to allow the hologram processing routine to consistently detect and track particles. From this overlaid image, characteristics of the settling dust can be observed visually. The mean particle velocity downward can be clearly seen, and the slight mean particle velocity to the left of the frame can also be detected upon closer inspection.

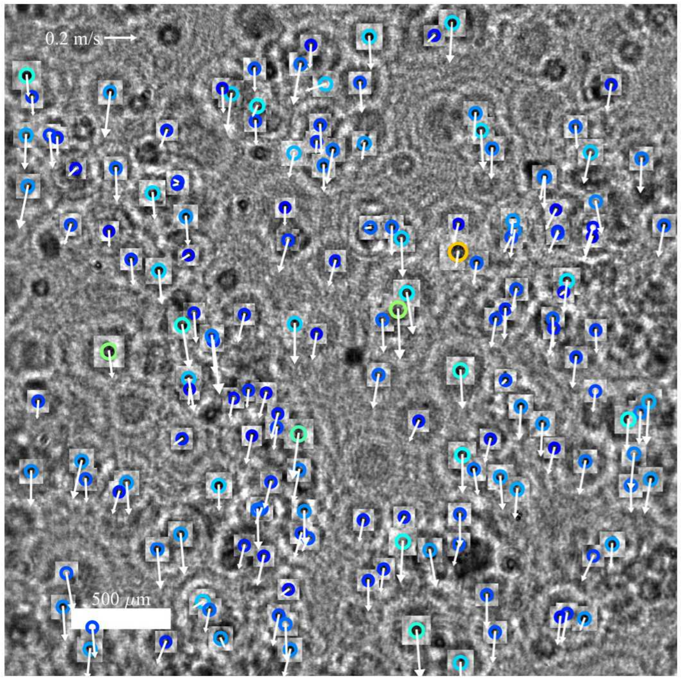


Fig. 4: Overlaid image of the dust particle flow field 1.12 s after the dispersion enters the field of view.

While the overlaid image is helpful for visualizing the dust particle flow field at a singular point in time, the corresponding size and in-plane velocity distributions seen in Fig. 5 provide statistical characterization of the dispersion over the processed time interval. Fig. 5(a) reveals a right skewed distribution of diameters with no particles under 45 μm detected. The in-plane velocity component distributions also faithfully capture the apparent motion in the overlay image while also characterizing the variation in particle velocities during the processed time interval.

To validate these results, the size distribution for the processed hologram sequence is replotted as a volumetric probability density function (pdf) and compared to a representative volumetric size distribution for the glass beads as measured by a purpose-built particle size analyzer (Beckman Coulter LS 13 320). The distributions are comparable, although the representative distribution reports the additional presence of particles smaller than 45 μm, a feature not captured by the volumetric pdf in Fig. 6. It is speculated that this discrepancy between the distributions arises from the fact that the volumetric pdf produced from the processed hologram sequence only represents the population of particles detected in the field of view, and not the entire dust population. Further analysis of these results can provide insight into the settling characteristics of the dispersion. During this time interval, smaller particles may still be dispersed higher up in the tube, while larger particles may have already descended to the bottom. Distribution statistics will be investigated over a wider range of time intervals to fully explore this phenomenon in follow on studies.

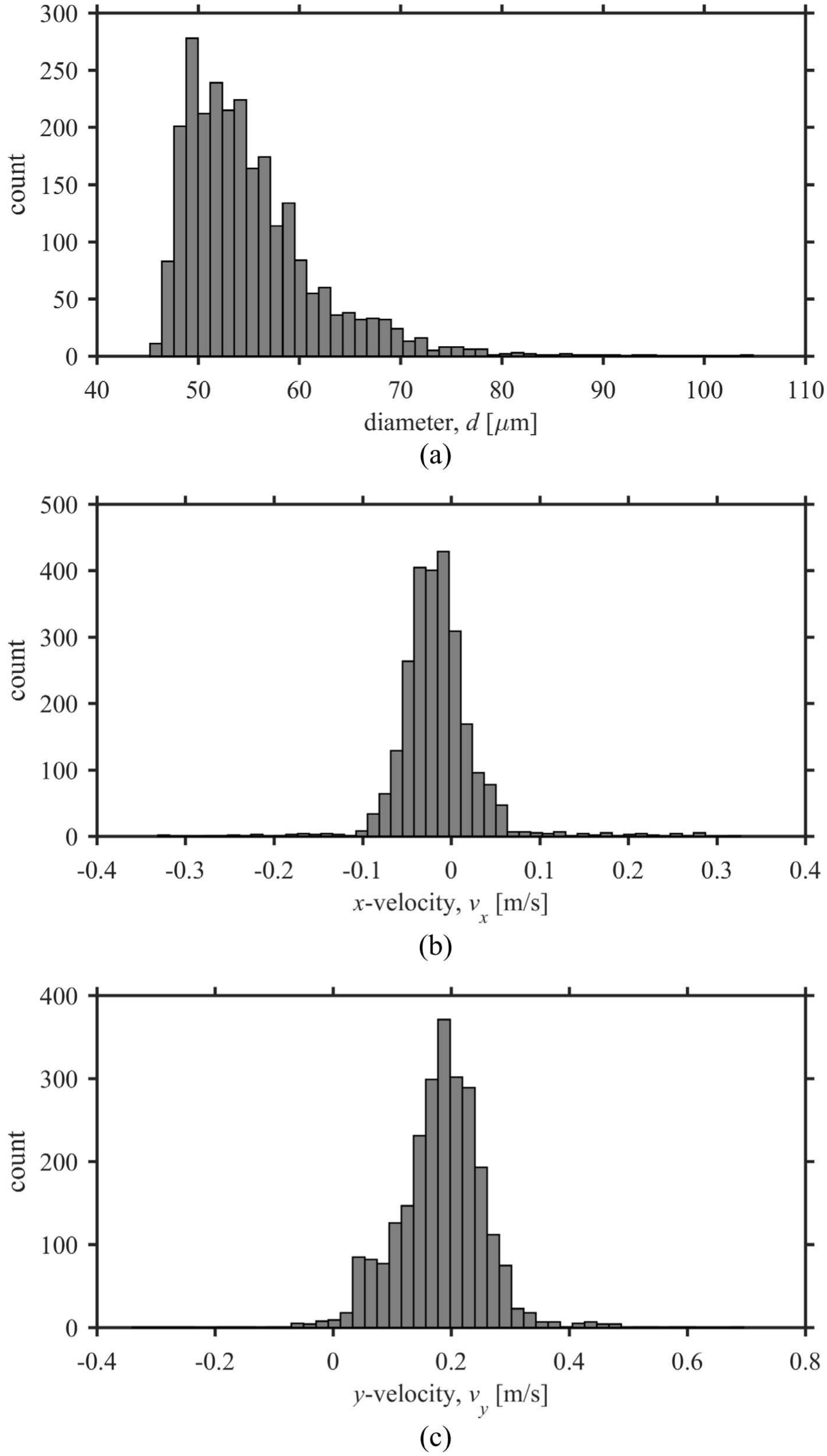


Fig. 5: Distribution of (a) size, (b) x-component velocity, and (c) y-component velocity for dust particles in the processed hologram sequence.

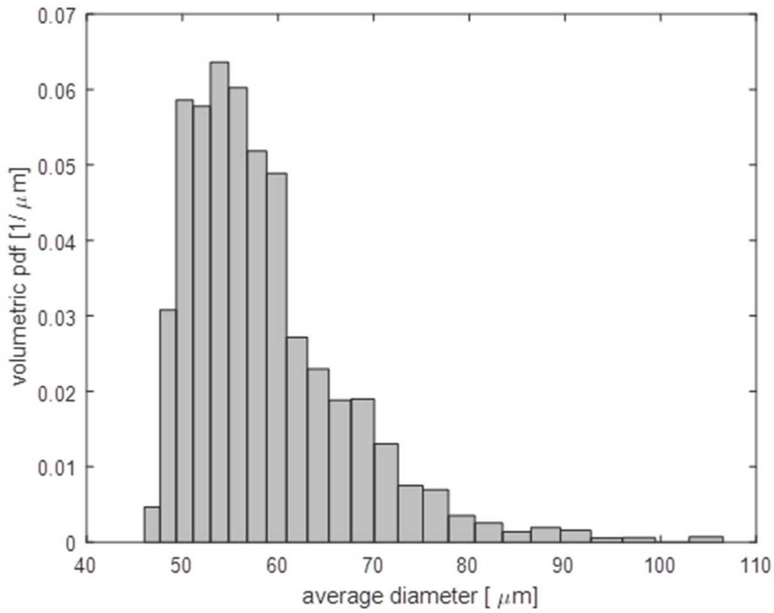


Fig. 6: Volume pdf for dust particles in the processed hologram sequence.

Successful imaging at earlier dispersion times represents challenges to fully implement DIH to dust dispersions in air. During a standard MIE test, a 120 ms delay between dispersion generation and spark initiation is typically applied. Strategies must therefore be implemented to accommodate successful collection and processing of holograms at this time. The high initial dispersion velocity of dust particles can be easily addressed by implementing higher frame frequencies. The nominal particle concentration can also be reduced to levels adequate for successful hologram processing. A balance however must be maintained between particle concentrations that are suitable for DIH and concentrations that are ultimately ignitable and hence meaningful with respect to the MIE testing. In addition to these challenges, quantitative particle flow field data will also be produced for an experimental configuration that includes the test electrodes in order to fully characterize dust dispersions in a Kühner MIKE 3 MIE apparatus in future studies.

4. Conclusions

The results of this experiment demonstrate the feasibility of dust particle flow field characterization in a Kühner MIKE 3 MIE apparatus via high-speed DIH. As a proof of concept, this work represents the first step towards full DIH dust characterization capability and the correlation of dust-specific flow properties with the MIE. Although the results of this experiment were achievable at suitably low dust concentrations in the field of view, quantitative dust particle flow field data must be successfully acquired at earlier dispersion times to apply DIH at standard MIE test ignition conditions.

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