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Shadowgraph technique applied to STARDUST facility for dust tracking: first results

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Abstract

The problem of dust resuspension in case of Loss Of Vacuum Accident (LOVA) in a nuclear fusion plant (ITER or DEMO like) is an important issue for the safety of workers and the security of environment. The Quantum Electronics and Plasma Physics Research Group has implemented an optical set-up to track dust during a LOVA reproduction inside the experimental facility STARDUST. The shadowgraph technique, in this work, it is applied to track dark dust (like Tungsten). The shadowgraph technique is based on an expanded collimated beam of light emitted by a laser (or a lamp) transversely to the flow field direction. Inside STARDUST the dust moving in the air flow causes variations of refractive index of light that can be detected by the means of a CCD camera. A spatial modulation of the light-intensity distribution on the camera can be measured. The resulting pattern is a shadow of the refractive index field that prevails in the region of the disturbance. The authors use an incandescent white lamp to illuminate the vacuum vessel of STARDUST facility. The light-area passes through the test section that has to be investigated and the images of the dust shadows are collected with a fast CCD camera. The images are then elaborated with mathematical algorithms to obtain information about the velocity fields of dust during the accidents reproduction. The experimental set-up together with a critical analysis of the first results are presented in this paper.

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Keywords: *Nuclear fusion plants, Security, Safety, Dust, Tracking, Radioactive, Computer Vision, Shadowgraph, ITER.*

1. Introduction

Dust production and mobilization is one of the key security aspects in the new generation tokamak (like ITER or DEMO). The dust is usually produced as a consequence of different types of plasma-material interaction (VDE, ELMs and disruption). It is well-known that dust occurring in events like LOVAs (Loss Of Vacuum Accidents) can generate reactive species in edge plasmas, arcing, explosive ejection and brittle destruction of surface imperfections, and nucleation of vaporized materials [1]. Particle sizes are typically small, in the range of 0,1 μm to 1000 μm. This particle size range raises three separate classes of safety concerns related to these toxic dust [2]: 1) these can be easily re-suspended (the decreasing particle diameter leads to dominance of fluid drag (~d^2) over gravity (~d^3) forces, but is important to notice that at the smallest of diameters, adhesive forces (~d) dominate and inhibit resuspension). 2) these are breathable and it represents a danger for workers and operators health [3-6]. 3) these are potentially combustible. Several experimental studies [7-23] demonstrated that the exchange flows depend on : 1) number, position, length and shape of breaches; 2) pressure and temperature conditions; 3) type of fluid. The Quantum Electronics and Plasma Physics Research Group of University of Rome Tor Vergata (QEP) has developed an experimental facility, STARDUST, that allows the reproduction of thermo-fluid dynamic conditions comparable to those expected in the Vacuum Vessel (VV) of nuclear fusion plants like ITER [11-18, 20-23]. In this work the QEP, in collaboration with the Grupo de Tratamiento de Imágenes (GTI) of Universidad Politécnica de Madrid, demonstrates the capability/suitability of STARDUST to collect images (by the means of shadowgraph technique) of tungsten re-suspended during a LOVA and to obtain information about the velocity fields and directions of tungsten. The experimental set-up and first results of images elaboration are presented and discussed by the authors.

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2. Shadowgraph technique: Experimental Set-up on STARDUST facility

The shadowgraph technique employs variation in refractive index to map dust velocity field in a flow. The images formation depends from the variation of the refractive index. In this case the passing rays of light, illuminating a specific are, are refracted and bent out of their original path. This phenomenon produces converging and diverging of light rays, which are collected by the fast camera. The main shadowgraph methods are: a) direct shadowgraph; b) focused shadowgraph. The authors use a Direct Shadowgraph in Diverging Light. The experimental set-up implemented on the STARDUST facility (see Figure 1) consists in the use of an incandescent white lamp that operates at 12 Volt with a current density variable in a range from 0 to 6 Ampere. A ground-glass is placed in front of the lamp to uniform the illumination area. The tungsten lamp has been chosen because the monochromatic light is undesirable for shadowgraph since it exacerbates diffraction fringing and mimics the effect of a too-small light source [29] and it is not possible to increase indefinitely the resolution and the sensitivity upon reducing the light source size (there is a limit due to the diffraction). A fast camera [24] is placed on the opposite window (in front of the light source) to collect images of the dust shadow during the LOVA reproduction.

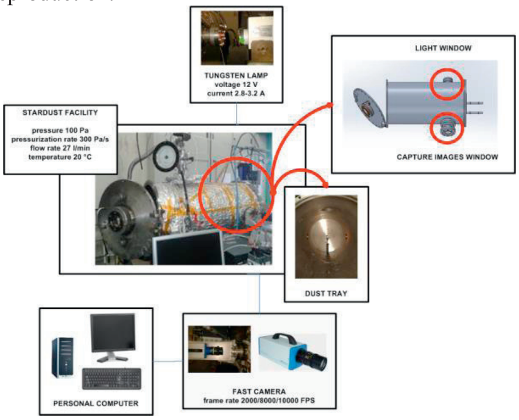

Fig. 1. Experimental set-up for shadowgraph

The dust used is Tungsten (W), whose characteristics are analyzed in [16]. The resulting images are composed of two part: a bright background and the shadow of dust.

3. Particles Detection and Tracking

The acquisition system is described above. A detail of an image acquired with the proposed experimental setup presented in Figure 2, where the shadows of the particles inside STARDUST allow the identification on a very bright background light source. The approach proposed in this paper aims to demonstrate that is possible to detect and track dust particles inside STARDUST as well as estimate their velocity and direction during the experiment. As shown in Figure 3 the proposed approach consists of two main steps: particle detection (PartDet) and tracking (PartTrack). Figure 2 shows that shadowgraph technique guarantees high contrast images (the unit of axes of figures 2,4 and 5 are in pixel, 1 pixel=0,02229 cm) This allows the detection of moving particles inside STARDUST, without a pre-processing phase, and this is the first huge difference with the images collected with the PIV (Particles Image Velocimetry) techniques [30,31].

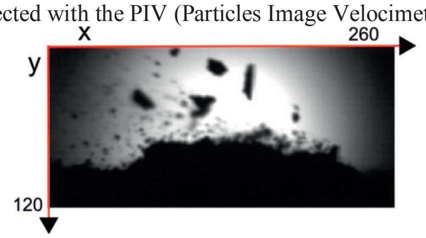

Fig. 2. Raw image acquired by the fast camera.

The PartDet block in charge of building a stable background model of the scene before that the experiment starts. The background model is based on the Mixture of Gaussian (MoG) approach presented in [25]. MoG guarantees for each pixel a multi-modal background, based on a mixture of Gaussian distribution, able to reduce temporal variation and flickering noise of the acquired images.

Fig. 3 Block Diagram of the particle tracking system.

The MoG is a two-step algorithm: in the first step, it is tested whether or not every incoming pixel value belongs to the background model by considering the distance between the current pixel value and the Gaussians mean value. In the second step, the model parameters are recursively updated with an online version of the Expectation Maximization algorithm (see [25] for more details). The resulting foreground binary image (indicated as FG_part in figure 3) is presented in figure 4. As it can be noticed, the proposed approach guarantees a good detection accuracy of the moving particles in the tank. The obtained foreground connected regions are filtered by considering their area in order to identify the small moving particles.

Fig. 4 Detected dust particles

In the large foreground region corresponding to an area densely populated by dust particles, it is not possible to clearly distinguish the several particles that compose it. Once this large region is detected it is tracked separately and its estimated velocity and other parameters are considered representative of all the particles that compose it. The regions containing the detected particles detections are processed by *PartTrack* step (fig.3) to estimate their trajectory and velocity. In particular, we propose a multi-object tracking algorithm based on Kalman Filter [27]. The Kalman filter is a recursive data processing algorithm that generates optimal estimates of the system state for linear systems with white Gaussian errors. In the proposed dust particles tracking system we model our dynamic system by considering three variables: the position of the detected particle, its velocity and its acceleration. The latter one is supposed to be almost constant during the first seconds of vacuum rupture (at the beginning of the experiment). A Kalman Filter is applied to each particle, thus allowing predicting the values of its state variables during the experiment. For each iteration, the predicted positions and the detected particles position are then associated by considering their closeness in the image plane. The Hungarian algorithm [28] is employed in order to solve the assignment problem, allowing tracking the same particles along the frames.

4. Results and discussion

The proposed Kalman-based approach has different advantages; in fact, it allows to independently modeling the dynamic behavior of each particle. Furthermore, it allows recovering miss-detected particles thanks to the prediction phase. In particular, according to the experimental conditions, we use a state model based on a constant acceleration of the particles in the first 1,5-2 seconds of the experiments. It is worth noting that when a new particle is detected and it has not been associated with any of the existing particle, it is considered as a new particle (it starts moving) and a new Kalman tracker is initialized for it. On the contrary, when a particle has not been associated with a detection for a long time, it is considered as "immobile" particle (it moves out of the camera field of view) then, the corresponding data are stored and it is deleted from the multi-object tracking framework. Figure 5 reports an example of a detected and tracked dust particle: the first detected particle's position is marked with a red square (see Fig. 5 (a)); the final particle's position is marked with a red circle (see Fig. 5 (b)). It has to be noticed that the particle trajectory reported in Fig. 5 is obtained by joining the particles position identified in the intermediate frames (25 in this example).

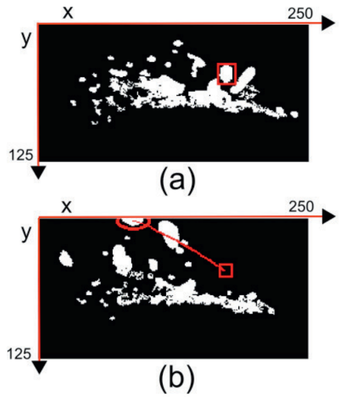

Fig. 5 Example of a tracked dust particle

The sequence analyzed is the one at 5000 fps simulating a LOVA at 300 Pa/s (see [11-18 and 20-23,32,33 for further information about the experiments]. The dust is tracked between the frames 377 and 802 that means a time range of 0,0754 sec to 0,1604 sec from the air inlet beginning (see table 1). After 0,1604 sec all the dust placed on the tray is in a huge part mobilized. In figure 6 dust particle moves at a maximum velocity of approximately 60-80 m/s. The velocity is calculated by the image processing considering packages of 25 images.

Table 1 Experimental data collected inside STARDUST

Time (s)	$T_{wall\ mean}$ (K)	T_{env} (K)	P_{in} (Pa)	FR (lit/min)
0,0754	278,19	280,24	172,35	3,16
0,1604	285,17	281,33	200,82	4,74

Legend:

- *1st Column : Time (in second) after the beginning of air flow inlet*
- *2nd Column : Mean value of wall temperature (in Kelvin) measured by thermocouples*
- *3rd Column : Mean value of STARDUST internal environment temperature (in Kelvin) measured by thermocouples*
- *4th Column : Internal pressure inside STARDUST (in Pascal)*
- *5th Column : Flow rate of pressurized air flowed inside STARDUST (Liter/minute)*

The dust velocities values have been compared with the one of the air, measured with pressure transducer arrays [15], in the same: 1) position of dust; 2) experimental conditions; 3) time window (see figure 6). The time range of the images sequence analyzed correspond to the following experimental data:

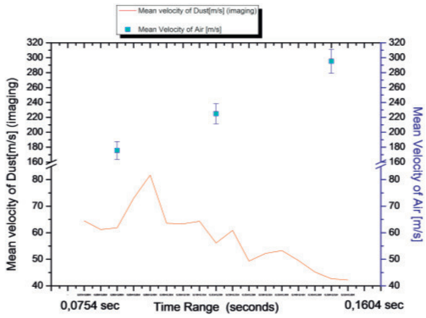

Fig. 6 Dust Velocity values measured at the beginning of airflow inlet compared to the velocity values of air.

The authors applied the techniques also to obtain the principal directions of the dust respect the horizontal plane of the tray (Figure 7) and get detailed information about the velocity field. The principal trajectories lie between 150° to 180°.

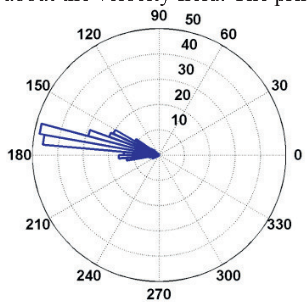

Fig. 7 Dust principal directions during the mobilization

5. Conclusions and future developments

The authors developed an experimental set-up to reproduce a LOVA that could be expected in a nuclear fusion plant like ITER. They acquired, with a high speed camera and a proper optical apparatus, image sequences of dust mobilized during the LOVA reproduction. The authors also developed a computer vision approach to derive data from the images by means of an image processing technique (in particular dust velocities and dust directions). The principal advantages, in the application of the shadowgraph technique, are: a) It allow to use a white lamp instead that a laser source (as in the PIV technique) and it means a faster preparation of the experiment. b) A better quality of the images in terms of resolution avoiding the pre-processing of the images during the computer vision phase. c) A better resolution of images also with bright dust (SS316). In the first phase of experiment dust velocities values are lower than the ones of pressurized air measured in the same point and at the same time with pressure transducer and this point has to be investigated. In order to associate the results from data imaging to the thermo-fluidodynamics property of the inflow air during the maximum velocity regime, these future upgrades have to be implemented: a) increase the field of view inside STARDUST by introducing new windows. b) Flow the air from the divertor region and collect images in order to reduce the direct impact of air on the dust so its velocity. c) Compare the velocities with those recovered with lower pressurization rates. d) Analyze the effect of adhesive forces that for the small particle dominate and inhibit the resuspension. e) Develop a scaling analysis to better reproduce a LOVA conditions inside the experimental facility.

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