Optical measurement of dust concentration field and mass resuspension rate applied to STARDUST-Upgrade

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Abstract. The production and resuspension of dust is a critical safety issue in several industrial fields. Thousands of dust explosions occur every year in Europe inside industrial plants, some of those accidents caused the death of about ten people and hundreds of injuries. Dust resuspension may also involve safety issues and hazards in nuclear power plants, especially in magnetic confinement fusion reactors, the TOKAMAKs, and in high-temperature gas-cooled reactors. Therefore, it is a necessity to understand how dust resuspension occurs and to develop numerical models to reproduce these events. An experimental facility has been built in the laboratory of the University of Rome “Tor Vergata” to study the resuspension of dust, STARDUST-Upgrade. This work shows a new experimental apparatus developed to measure two properties of dust resuspension: the concentration field and the mass resuspension rate. These measurements are achieved through a light absorption-based method, exploiting the Beer-Lambert law. The measurements are performed under six different conditions. The results are analysed and discussed, in order to understand the advantages and the limits of this technique.

1. Introduction

The resuspension and mobilisation of dust inside enclosed environments may lead to dangerous events and hazards. The most famous and critical dust hazard is the dust explosion [1]. This phenomenon threatens several industrial application fields, from coal to food industries [2]. Basically, the dust explosion may occur when a combustible dust (sugar, flour, coal, starch, steel, etc.) resuspends inside an enclosed environment, where there is an oxidant, usually air, and it reaches a concentration value that ranges between the Lower Explosive Limit (LEL) and the Upper Explosive Limit (UEL). If an ignition source (sparks, flame, etc.) is present in that environment, the explosion occurs [3, 4, 5]. Another important safety hazard is the radioactive and toxic dust release from the nuclear power plants. Especially in fusion nuclear reactors, a large production of dust may occur because of Plasma-Material Interactions [6, 7, 8]. A part of this dust deposits on the wall and on the divertor of the vacuum vessel. This dust will be compounded mainly by the first wall materials, that could be carbon, tungsten and beryllium. Beryllium is toxic. Carbon has a large retention of hydrogen, and thus tritium. Furthermore, dust will be subject to neutronic flux. It will be toxic, radioactive and also explosive [9, 10, 11]. In case of Loss Of Vacuum Accidents, the deposited dust may resuspend and mobilise inside
the reactor. Several are the possible consequences of these events. At first, the plasma will turn off because of impurities (air and dust), involving a shutdown of the reactor for a large period, where energy will not be generated. A dust explosion may occur inside the vessel. The vacuum vessel is an enclosed environment, the air is the oxidizer, dust is combustible and, at the beginning of the experiment, inside the vessel there are very high temperatures because of the large heat fluxes. Furthermore, a release of dust may occur after the LOVA, since the vacuum vessel is no more isolated from the external environment [10, 12, 13].

The study of the LOVA has been investigated for years by the Quantum Electronics and Plasma Physics (QEP) research group of the University of Rome “Tor Vergata”, by means of a scaled facility named STARDUST-Upgrade. STARDUST-U is a small vacuum vessel where LOVAs in different conditions can be replicated. A deep analysis of the fluid dynamics of a LOVA event has been performed and single-phase numerical models to replicate the LOVA have been developed and validated [13]. The development of these models allowed to replicate a Loss Of Vacuum Accident inside a real size vacuum vessel. The evaluation of the pressurization rate, the local Mach number and the friction velocity on the walls has been performed and a deeper understanding of the problem has been provided [14].

The next step is the analysis of the dust resuspension and the development of a multiphase model able to take into account also the dust behaviour. The study of dust resuspension inside STARDUST-U is allowed by optical techniques. In the last two years, the measurement techniques of dust particle velocities have been developed and improved, leading to the best experimental apparatus and analysis method to evaluate the velocity of dust inside STARDUST-Upgrade [15, 16]. This work focuses on the measurement of the concentration field and resuspension rate. Both characteristics are essential to provide dust resuspension properties to compare with a multiphase model. Furthermore, a deep understanding of resuspension phenomena could be lead to the development of solutions, systems, devices and best practices to prevent dust hazards or to limit its effects [17].

2. Materials and Methods
This section describes the experimental apparatus used to replicate the dust resuspension inside a vacuum vessel in case of loss of vacuum accidents. Then, the method used to evaluate the concentration field and the resuspension rate is shown and discussed.

![Figure 1. Scheme of the optical setup to measure dust concentration and position of the inlet valves.](image)

2.1. STARDUST-Upgrade – LOVA replication
STARDUST-Upgrade is the experimental facility built to reproduce the Loss of Vacuum Accidents which may occur inside a TOKAMAK. It is a stainless steel cylindrical vacuum vessel that can reach a minimum vacuum pressure of 30 Pa. The internal chamber size has a radius of 24.5 cm and a length of 92.0 cm. Quartz windows are placed in specific regions of the chamber to interface optical measurement devices. A vacuum pump produces the vacuum inside the vessel. Two pressure gauges monitor the pressure inside the vessel as well as four thermocouples allow to measure the temperature.
When the desired initial conditions are reached, an electro-pneumatic valve is closed, and the vessel is mechanically isolated from the vacuum pump and the external environment. Then, one of the six valves is opened and the air flows inside the chamber. If the flow-meter is used, it is possible to replicate an accident with a specific pressurization rate. A more complete and detailed description of STARDUST-U apparatus and functioning can be found in literature [13].

The last experimental campaigns of STARDUST-U are aimed at measuring the dust re-suspension and the mobilization during these accidents. A shadowgraph-like apparatus has been developed to track the velocity of “dark” particles [1]. Figure 1 shows a scheme of the “Shadowgraph” apparatus inside STARDUST-U. The light emitted by a laser is expanded by a beam-expander, compounded by two plano-convex lenses. Thus, the large laser beam crosses the vacuum vessel and interacts with dust particles. Then, the light is collimated by a plano-convex lens inside the fast camera. The image acquired is a white background image with dark dust particles and bulk dust. Figure 2 shows a frame when dust is not resuspending.

![Figure 2. Frame obtained through the optical setup. The image represents the dust deposited on the tray.](image)

Dust can be placed inside STARDUST-Upgrade in several different positions of the vacuum vessel, using a mechanical support. In this work, six different LOVAs have been reproduced, using two different inlet valves, valve E and F, and placing the dust at the center of the vessel at different heights. The dust mass on the tray is measured by a weighting scale before and after each experiment to evaluate the percentage of resuspended dust. Table 1 describes some information of each experiment: the acronym used to refer to the experiment, the valve used to allow the intake of air, the tray height, the number of frames recorded by the camera, its frame rate and the resolution of the camera.

| Acronym | Valve | Dust tray height | Number of frames | Frame rate | Frame size       |
|---------|-------|------------------|------------------|------------|------------------|
| V_E_h15 | E     | 15 cm            | 9000             | 5000 fps   | 1280x128 pixels  |
| V_E_h10 | E     | 10 cm            | 9000             | 5000 fps   | 1280x128 pixels  |
| V_F_h23 | F     | 23 cm            | 9000             | 5000 fps   | 1280x128 pixels  |
| V_F_h20 | F     | 20 cm            | 9000             | 5000 fps   | 1280x128 pixels  |
| V_F_h13 | F     | 13 cm            | 9000             | 5000 fps   | 1280x128 pixels  |
| V_F_h8  | F     | 8 cm             | 9000             | 5000 fps   | 1280x128 pixels  |

2.2. Concentration and resuspension rate measurement method
The evaluation of dust concentration field is performed by an absorption-based method. These methods use the Beer-Lambert law, which describes the absorption and the transmittance of light through the matter. This equation has an exponential trend and, for one absorbing species, can be written as follow:

\[
\frac{dl}{l} = -\sigma \alpha c dz \rightarrow \frac{l}{l_0} = e^{-\int_0^l \sigma \alpha c(x,y,z,t)dz} = e^{-\sigma \alpha c \bar{l}}
\]

(1)

Where \(l\) is the transmitted light intensity, \(l_0\) is the light intensity received when there is not dust, \(\sigma \alpha\) is the absorption cross-section, \(l\) is the path length and \(c\) is the dust concentration. From this equation, it is impossible to obtain the exact concentration in a specific point \((x, y, z)\), where \(x\) and \(y\) are the horizontal and vertical coordinates of the image, orthogonal to the light direction, that is \(z\). The
average concentration \( \bar{c}(x, y) \) can be computed if it is possible to assume that the absorption cross-section does not vary in significant ways with the direction \( z \) and the concentration \( c \). This hypothesis is acceptable only if dust concentration does not vary too much. In the resuspension event, it does not occur frequently. Thus, the measurements that we provide in this paper are affected by a significant error. However, this approach could be interesting and useful to achieve some information about the dynamics of dust resuspension. Thus, assuming a not variable absorption cross-section, the equation (1) can be written as:

\[
\bar{c}(x, y) = \frac{1}{I_{\sigma}(x,y)} \ln \frac{I_0(x,y)}{I_l(x,y)}
\]  

Consider a reference case, where the dust concentration is known in each point of the frame. The case corresponds to deposited dust before the resuspension, such as figure 2. In this case, the dust concentration can be assumed equal to the maximum packing where there is dust and zero somewhere else. Thus, it follows:

\[
I_{\sigma}(x,y) = \frac{1}{c_{\text{ref}}(x,y)} \ln \frac{I_0(x,y)}{I_{\text{ref}}(x,y)}
\]  

Where \( I_{\text{ref}}(x,y) \) is measured in case of no-resuspension and \( c_{\text{ref}}(x,y) \) is the concentration field in refererence case. Thus, combining equation 2 and 3, it follows:

\[
\bar{c}(x, y) = c_{\text{ref}}(x, y) \frac{\ln \frac{I_0(x,y)}{I_l(x,y)}}{\ln \frac{I_0(x,y)}{I_{\text{ref}}(x,y)}}
\]  

Thus, the measurement of dust concentration needs the evaluation of three intensities and thus three images. The first is the background image, obtained when there is not dust. The second is the image of the deposited dust, obtained before resuspension starts, so when the dust is still deposited on the tray. The last one is the resuspension dust frame, that represents an instant of the resuspension phenomenon. By acquiring several frames during the resuspension phenomenon, it is possible to obtain the concentration field over the time.

A widely used parameter to evaluate the resuspension phenomenon is the resuspension rate (\( \Lambda \)), that describes the percentage of dust mass resuspended over the time. It can be written as follows:

\[
\Lambda = -\frac{1}{M_0} \frac{dM(t)}{dt}
\]  

where \( M_0 \) is the initial mass of the deposit while \( M(t) \) is the mass at the time \( t \). The mass \( M(t) \) can be calculated as the integral of the concentration over the volume above the tray, where the dust is deposited before the resuspension:

\[
M(t) = \int_V c(t) dV = \sum_{i=1}^{N} c_i(t) S_i t_i = S I \sum_{i=1}^{N} c_i(t)
\]  

where \( S \) is the area of one pixel. Therefore, the re-suspension rate can be written as follow:

\[
\Lambda(t) = -\frac{1}{M_0} \frac{dM(t)}{dt} = -\frac{1}{M_0} \frac{M_j - M_{j-1}}{\Delta t}
\]  

where \( \Delta t \) the time interval, \( N \) the number of pixels and \( j \) is the frame at the time interval \( t \).

3. Results

In errore. L’origine riferimento non è stata trovata. has been shown the concentration field of the experiment V_E_h1.5 at three different time intervals: t=0.00 s, 0.20 s and 0.25 s. These images use a scale of colour to indicate the concentration value in each pixel. The red pixel indicates a maximum packing of the dust (\( c/c_0=1 \)) while the dark blue means that there is no dust (\( c/c_0=0 \)). The colour scale is linear. The first frame represents the initial condition, where the dust is entirely deposited (red
region). The other two frames show a small quantity of dust re-suspended clouds. There are both large agglomerates and dust. In these frames, the air flows from the right to the left.

![Image of dust concentration field](image1)

**Figure 3.** Three frames showing the concentration field of the experiment V_E_h15 at the time: 0.00 s, 0.20 s and 0.25 s.

Figure 4 (a) shows the relative resuspension of dust above the tray region. The blue points are the measure without the application of a filter, while the red line is the variable smoothed through a moving-average filter. The relative concentration begins with a value equal to one and decreases when the re-suspension occurs. Note that resuspension starts after 0.1 s. This is due to two reasons. At first, the fast camera acquisition begins 200 ms before the valve opening. Then, a delay between the valve opening and dust resuspension is due to resuspension behaviour. Basically, the air dynamic pressure must reach a value large enough to involve aerodynamic forces, drag and lift, larger than the adhesion and cohesion forces of particles. The teal line is the resuspension rate. It is calculated through eq. 6 using the smoothed value of relative concentration. The relative concentration has a decreasing trend with some peaks where the concentration arises. These peaks are due to the passage of re-suspended dust above the deposited dust or the tray. These peaks involve also negative values of the resuspension rate and they involve an error on the evaluation of dust resuspension rate.

![Image of resuspension rate](image2)

**Figure 4.** Re-suspension rate, relative mass on the tray and relative re-suspended mass in function of time.

Figure 4 (b) shows the relative resuspended dust. It is calculated as one minus the relative concentration (c/c0). This graph shows a trend similar to the resuspension trends found in literature.
[19], i.e. an exponential tendency with a horizontal asymptote to the maximum re-suspended concentration. The last value indicates the total percentage of resuspended dust.

![Graph showing comparison of re-suspended dust measured through the optical method and the weighing scale.](image)

**Figure 5.** Comparison of re-suspended dust measured through the optical method and the weighing scale (a). Percentage of resuspended dust versus time in each experiment (b).

The re-suspended dust calculated with the optical method and with the weighing scale are compared in Errore. L'origine riferimento non è stata trovata. (a). Small differences are reported in three experiments: V_E_h15, V_F_23 and V_F_h20. In the other three experiments, the percentage of re-suspended dust is underestimated by the optical method. However, an underestimation of the total resuspended dust is expected because of the maximum acquisition time of the fast camera. In fact, the fast camera is able to acquire images for a time not longer than 1.8 seconds in case of the set operative parameters (9000 frames, 5000 Hz and a resolution of 1280x128 pixels). Since the resuspension occurs along the whole experiment, the optical method misses the remaining seconds (the entire experiments last more than 30 seconds). However, the larger mass of dust resuspends in the first seconds of the accident, since the pressure gradient is very large, and high velocities are reached inside the camera. After a few seconds, the air flow slows down because the vessel is pressurising. Thus, it is expected that increasing the acquisition time of about 5 seconds, the method could be able to measure the entire resuspension event. The influence of the acquisition time can also be observed in figure 5 (b), especially by analysing the derivative of each trend at the end of the measurement. V_F_h23 and V_F_h20 have a flat trend when $t$ is equal to 1.8 seconds. Thus, a further resuspension is not expected after 1.8 seconds. This last sentence is verified in V_F_h20 and V_F_h23 measurements that return an accurate result. When the trend is not constant, it is expected that dust resuspension occurs also after the optical measurement time and the error committed by the optical method should increase with the derivative of the trends. It is validated in the case of V_F_h13 and V_F_h8. In the case of V_E_h15, the value at the end of the measurement agrees with the expected one. However, the derivative is not zero, then the trend is not constant, and an overestimation may occur if a larger acquisition time was performed. V_E_h10 underestimates the resuspended dust, maybe due to an instantaneous passage of dust in front of the camera.

4. **Conclusions**

STARDUST-Upgrade is an experimental scaled facility to reproduce loss of vacuum accidents, that may threat the safety of fusion reactors. STARDUST-U allows to reproduce, measure and analyse the resuspension and mobilisation of dust in different conditions. The understanding of these phenomena is useful also to develop systems and solutions to prevent safety issues related to dust resuspension,
such as dust explosions in industrial plants. STARDUST-U has been provided with an optical measurement apparatus to track the velocity and the concentration fields of dust as a function of time.

This work shows the first results obtained with the concentration measurement technique. The technique is based on an absorption method. Assuming that the larger is the concentration of dust, the lower is the transmitted light (Beer-Lambert law), the dust average concentration along the light path can be evaluated. These measurements are performed without considering the connection between the absorption cross-section and the dust concentration, and it may involve a relevant error, especially in case of dust resuspension, when the concentration ranges from the maximum value to zero. Otherwise, there are no other techniques that can be used with STARDUST-U to evaluate the resuspension and that may return more accurate results.

The experiments show the results that can be obtained with this technique. The information concerning the concentration field is obtained by an image that uses a colour scale to represent the concentration value. When there is not dust moving, the difference between the dust and the background is very clear. Once the phenomena of dust resuspension began, different kinds of structures can be observed: small particles, agglomerates and particle clouds. Combining the dust concentration with the velocity fields may be useful to investigate how resuspension occurs during a LOVA. Furthermore, global parameters, such as resuspension rate and resuspended mass can be calculated. The evaluation of the resuspension rate is fundamental to understand the flow properties that govern this parameter, in order to develop and validate a numerical resuspension model that work accurately during these events.

Future experimental campaigns will be performed to understand the influence of each boundary condition on the capability of dust to resuspend. Thus, multiphase numerical models will be performed and compared with the experimental data.

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