ECART analysis of the STARDUST dust resuspension tests with an obstacle presence

Sandro Paci[1], Bruno Gonfiotti[1], Daniele Martelli[1], Maria Teresa Porfiri[2]

[1] *University of Pisa, DICI, Largo Lucio Lazzarino 1, 56126, Pisa, Italy*
[2] *ENEA, FSN Department, via E. Fermi 45, 00044 Frascati, Roma, Italy*

ABSTRACT

To validate dust resuspension models in fusion like conditions, different experimental campaigns in the STARDUST facility were performed at ENEA laboratories Frascati (I). In the first campaign, resuspension of Tungsten (W), Carbon (C) and Stainless Steel (SS) dusts was investigated in an "empty tank" configuration, while resuspension of the same dust types in presence of an internal obstacle was studied in the second campaign. In this work, focalized on the ECART code validation, the assessment of the code "force balance" resuspension model against the data obtained during the second campaign is performed. ECART was able to provide a good qualitative and quantitative description of the resuspension phenomena so a further step in its validation has been achieved. Further improvements for the ECART resuspension model have been also highlighted, as the necessity to treat "particle clusters" and their aggregate movements.

Keywords: dust resuspension; ECART; STARDUST; ITER

1. Introduction

For fusion devices like International Thermonuclear Experimental Reactor (ITER) or DEMOnstration Power Station (DEMO) activated/toxic dust mobilization is one of the main safety concerns [1]. These dusts can be mobilized during a Design Basis Accident (DBA) as a Loss of Vacuum Accident (LOVA) and can be transported outside the Vacuum Vessel (VV) towards the confinement building and the external environment. During the ITER licensing process [2], a very conservative hypothesis of a complete mobilization of the dust inventory was assumed in the accident analyses assessment. Notwithstanding the expectation that DEMO dust inventory can be maintained no higher than that of ITER (lower erosion rate of plasma-facing surfaces and more stable scenario with fewer disruptions), resuspension is still an open safety issue [1]. The licensing process requests reliable simulation codes and this paper, on validation of the ECART code [3] (originally designed for safety analysis in fission nuclear plants but able to face fusion applications [4]) focuses on the investigation of its resuspension model. Several experimental tests have been conducted in Europe [5], US [6] and Japan [7] to relax the assumption of a complete dusts mobilization and to analyse resuspension phenomena in accident conditions expected for a fusion machine. As part of these efforts, different campaigns [8], [9] have been performed in the Small Tank for Aerosol Removal and DUST (STARDUST) facility, to build a base of code validation data in a heated volume at very low pressure.

Different models to predict aerosol resuspension are implemented in the various codes for the analysis of a severe accident in nuclear reactors [5]. Such models can be subdivided into two main categories: mechanical "*force balance*" and dynamic "*energy balance*" models. In the first category, particles mobilization basically occurs if calculated aerodynamic forces exceed adhesive ones. The semi-empirical ECART model [5], the MELCOR liftoff model [10] and the ASTEC one [11] are examples of this "force balance" approach. In turn, for "energy balance" models, particles resuspension occurs if enough energy is transferred to particles by the motion of the surrounding flow. Reeks and Hall "*Rock'n'Roll model*" and its following improvements [12] are examples of this category, considering not the forces but the momentum due to aerodynamic forces. However, most of these models were developed basing on conditions typical for a Light Water Reactor (LWR) primary system (i.e., pressure higher than atmospheric and high velocities) and only few of them have been validated for fusion applications [5]. Among these models, the ECART one, although less sophisticated respect to "energy balance" model, is able to roughly consider all the main phenomena of resuspension process and that is way it was one of the most extensively applied [4]. In this model, for each dust granulometry group, adhesive and aerodynamic forces are calculated at each time-step according to local thermal-hydraulics conditions. Resuspension occurs if the resulting force for the considered group – difference between adhesive and aerodynamic forces – exceeds zero and the number of particles of the group re-suspending each second – the "resuspension rate" – is empirically evaluated according to resuspension rates measured in several tests. Its main limitations affecting the simulation of STARDUST tests are: 1) dust population keeps same dimensions during all the transient (no agglomeration occurs for deposited particles, as on the contrary shown for W dust in STARDUST); 2) no particle cluster effects simulated, capable to increase the resuspension of smaller particles [5] (in a "cluster", a big particle - resuspended under current flow conditions - moves transporting surrounding particles, aggregated to the big one, even if these particles should not move in the current flow conditions).

author's email: sandro.paci@ing.unipi.it

2. Results of the second STARDUST experimental campaign

STARDUST facility [8] consists in a small horizontal cylindrical steel vessel (0.17 m^3), heated by electrical resistances (Fig. 1). Different types of dusts could be initially placed on a tray located in three different positions, discussed in the following, and compressed air can be injected through two lines: inlet A representing conditions equivalent to a of loss of vacuum through a VV equatorial port, while inlet B through the machine divertor port. Tank pressurization rate was 300 Pa/s (about 27 l/min of air), representative of ITER VV pressurization during the first seconds due to a small LOVA of 0.02 m^2 size [13]. Three commercial dusts were utilized [8] similar to what is foreseen currently in ITER, except C dust deriving from an old design of divertor walls that foresaw Carbon Fiber Composite (CFC) material. Dust masses employed in each test were 5.0 g for W and SS, while only 2.0 g were used for the lighter C, in order to reproduce a superficial density as expected in ITER. W particles, and in some extent also C ones, shown the tendency to immediately agglomerate on the tray. This behaviour is relevant for the following resuspension phenomena. Due to this agglomeration, it was possible to form similar dust heaps only for SS tests while W and C piles were geometrically different in each test. The spreading of experimental results pushed the execution of reiterated tests for each set of boundary conditions (air inlet, dust type and tray position).

The experimental results from the first campaign [8], [14], with an empty tank to maximize the resuspension, demonstrate that the complete resuspension assumption was too conservative. As a matter of fact, an accidental air ingress inside the VV faces different obstacles, as divertor cassettes. Furthermore, as shown by different experiments in old tokamaks, the biggest fraction of dusts deposits on divertor surfaces [15]. Hence, the air ingress through lower divertor ports is the most significant scenario for dust resuspension. For these reasons in the second STARDUST campaign, a semi-cylindrical steel obstacle, similar to a cradle, was positioned on the tank bottom to simulate effects related to the air motion caused by the divertor presence. A small bridge welded inside the obstacle represents the divertor dome. This obstacle is supported by four small cylindrical pins and forms, respect to the tank bottom, a partial annular narrow channel, having a width of 9 mm. Three different spatial positions for the tray (initially containing the dusts) were investigated: 1) under the obstacle, on tank bottom in the center of the narrow channel, to investigate resuspension from VV zones under the divertor (only the data for this position will be discussed in the following); 2) inside the obstacle, on its internal bottom part to simulate dusts deposited in the zone inside the divertor; 3) over its small bridge, to act as dusts in the zone over the divertor dome (practically no resuspension was measured for both the last two positions). Data for the "under the obstacle" position have been compared vs. the results of the STARDUST first campaign [8], in order to evaluate the obstacle influence. The comparison (Figure) highlights as the obstacle practically does not affect the very low resuspension values (below 1%) for inlet A tests. On the contrary, in all the inlet B tests with obstacle, C and SS mobilized masses were lower than the values obtained without obstacle, whit an unclear opposite behaviour shown for W dusts.

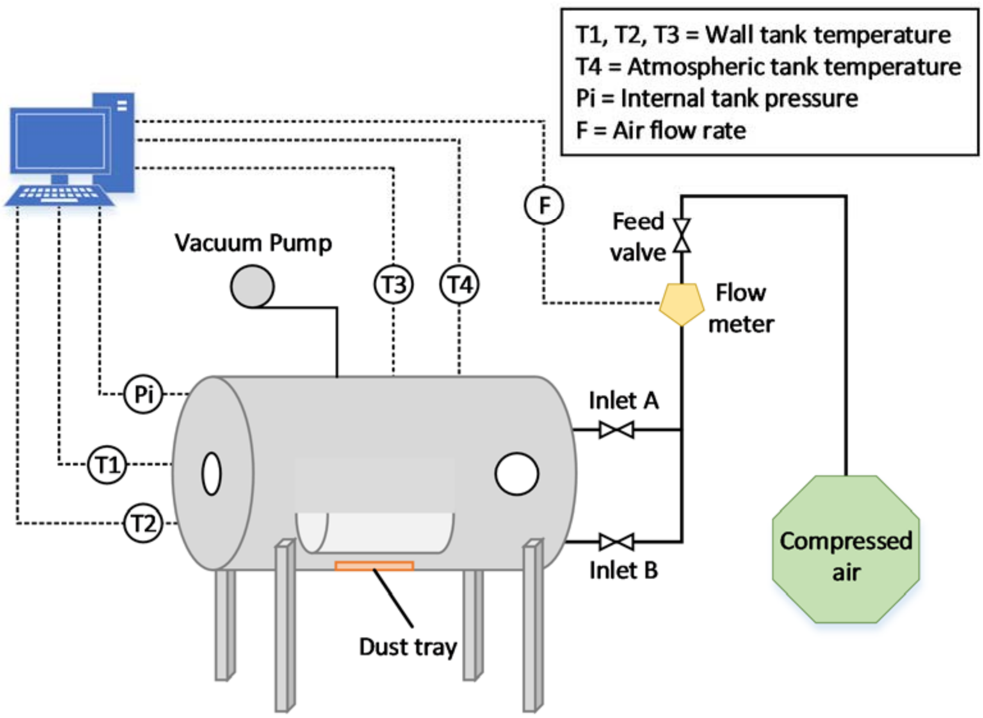

Figure 1: Layout of the STARDUST facility in the second campaign.

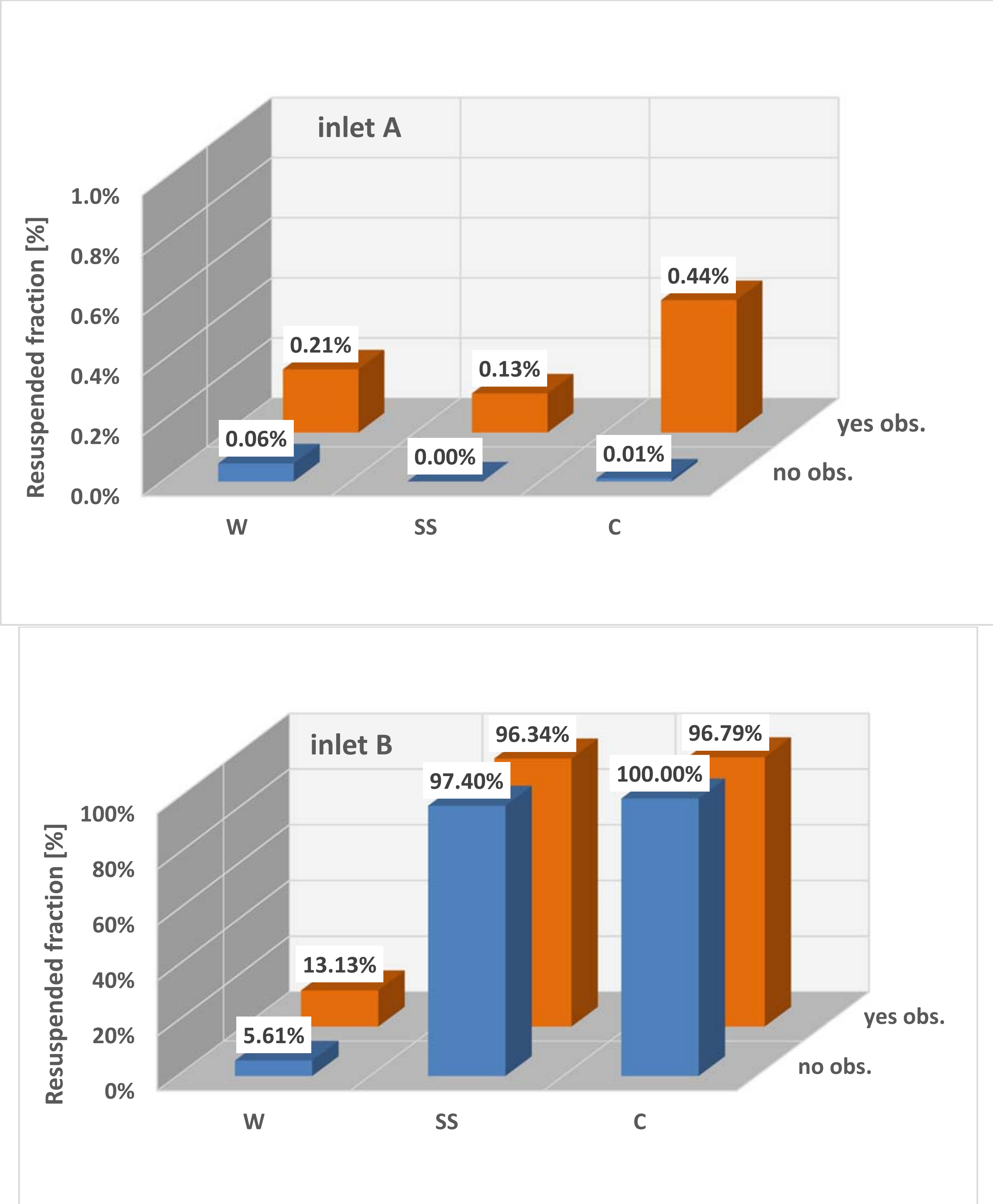

Figure 2: Influence of the obstacle presence for tray on the bottom of tank for the two inlets.

These differences, in particular for C and SS dusts, are linked to the obstacle presence, reducing the velocity magnitude over the dust tray, but also at the initial strong agglomeration of W dusts on the tray that, together with the experimental uncertainties, makes difficult also the reproducibility of these W tests [8]. Summarizing all the data from the two STARDUST campaigns, for the lower injection B about a practically complete resuspension (over 96%) is always highlighted for SS and C dusts initially on the tank bottom (lower values - from 5% to 13% - have been measured for W) while values always lower than 1% were always measured in the inlet A tests.

3. CFD/ECART analysis

STARDUST simulations have been performed employing the methodology utilized in previous works [14], [16] i.e. preliminary calculations by a Computational Fluid Dynamics (CFD) package (ANSYS Fluent and STAR-CCM+) to maps the velocity fields in the tank followed by ECART calculations to evaluate the dust resuspension. Practically, velocity magnitudes characterizing the air moving over the tray calculated by CFD tools where utilized as boundary condition by ECART resuspension model. CFD analysis have been performed for the two inlets, simulating the obstacle presence, employing identical boundary conditions and 3D meshes. For inlet A, in comparison to previous CFD calculations for the empty tank [8], [16], [17], velocity magnitude results slightly lower (about 5 m/s). For inlet B values from 30 m/s to 60 m/s in the central region under the obstacle are shown, again lower than empty tank velocities (about 50 - 120 m/s). After this comparison, a trimmed mesh was generated to investigate the influence of mesh typology, utilizing only STAR-CCM+. Employing this mesh relevant magnitude differences are shown in the narrow region under the obstacle. For inlet A, velocity is now about 20 m/s in the channel center. Moreover, for inlet B, velocities over 100 m/s at the channel inlet and about 70 m/s in its centre are now predicted. These conservative results (worst conditions for resuspension) were employed in ECART.

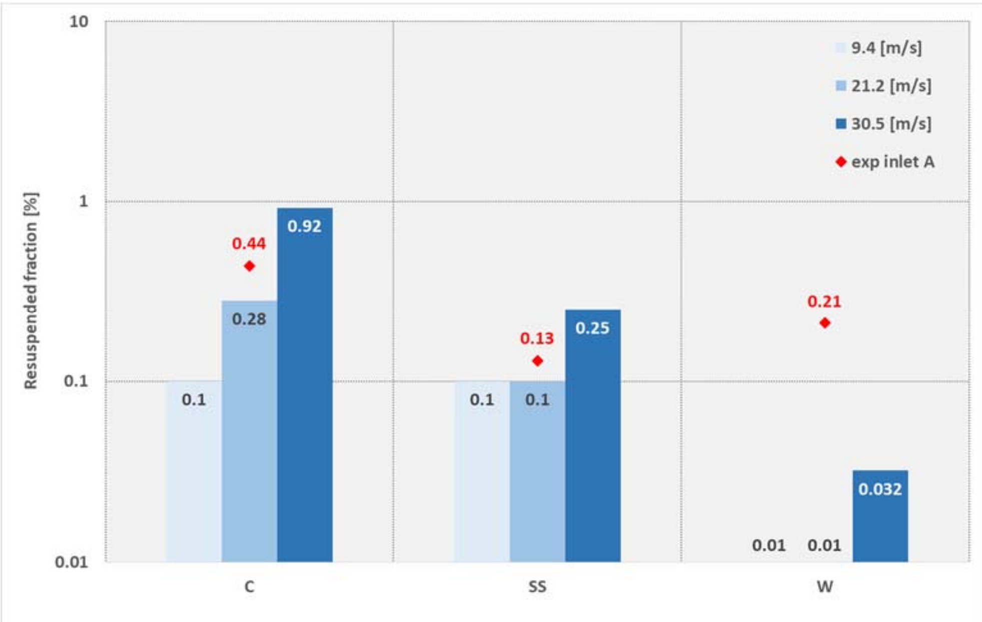

Figure 3: ECART vs. experimental resuspension data for inlet A tests.

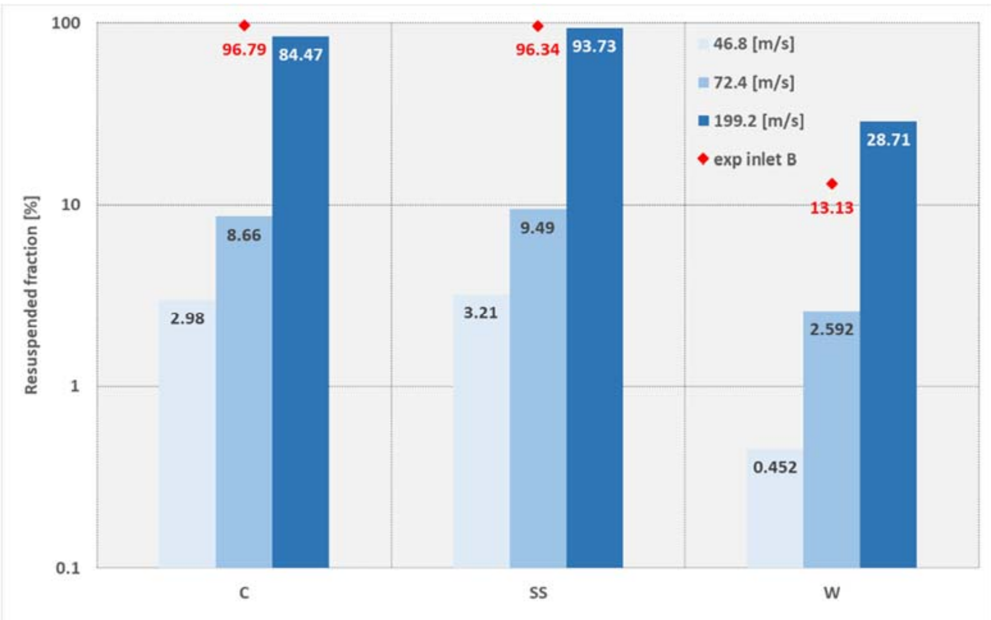

Figure 4: ECART vs. experimental resuspension data for inlet B tests.

To analyse the influence of velocity module on ECART predictions, three different velocities over the tray were employed for each inlet (in each group the central value is very near to the CFD one at the channel center while the other two values characterize the inlet and the exit of this channel), respectively 9.4, 21.2 and 30.5 m/s for inlet A (Fig. 3) and 46.8, 72.4 and 199.2 m/s for inlet B (Fig. 4). Different granulometries were numerically investigated for W tests (characterized by a strong agglomeration). From Scanning Electron Microscopy (SEM) analysis [8], W granulometry was characterized by a mass mean radius (MMR) equal to 0.25 μm nevertheless, ECART showed quite poor predictions assuming this SEM value. Only employing largest granulometries ECART predicts comparable but higher results (about 25% of resuspended mass at the highest velocity) compared to experimental data (about 13%) for inlet B. For inlet A, practically no resuspension (always well below 0.5%) is experimentally showed and confirmed by ECART. Reasons behind these under-predictions can be found on the agglomeration of W particles, which lead to a fast and important increase of their size, not simulated by the ECART model. On the contrary, only SEM granulometries were employed for C and SS dusts. All the experimental results highlight as the flow through inlet A (Fig. 3) practically does not cause resuspension (always lower than 0.5%), while air ingress through inlet B (Fig. 4) on the contrary leads to a practically complete resuspension. ECART is now able to correctly predict resuspension but, for inlet B position, also imposing the higher velocity (about 200 m/s), a slightly underestimation is shown (about 85% vs. 96.79% for C and 93.73% vs. 96.34% for SS).

3. Conclusions

In the present paper results obtained by the ECART code on different dust resuspension tests executed in the STARDUST facility have been reported. Main experimental and numerical achievements on resuspension phenomenology have been found to be quite in agreement because:

a) a negligible resuspension (below 1%) is always shown in the facility and by ECART when the pressurization flow is through the central inlet A, representing a VV equatorial port, result independent on tray position;
b) a negligible resuspension is also shown during all the tests with the tray inside the obstacle or over its bridge when the air flow enters through the lower inlet B, simulating a divertor port;
c) a very strong resuspension is on the contrary shown and confirmed by ECART when air enters through inlet B, for tests with the tray placed on the tank bottom.

Therefore, it can be stated that ECART resuspension model is able to provide a good qualitative and quantitative description of dust resuspension in conditions similar to a small LOVA in a fusion plant. So, a further step in ECART validation for its application to safety analysis of fusion installations has been achieved. Further improvements for the ECART resuspension model have been also highlighted, as the necessity to treat the formation of "particle clusters" and their aggregate movements. Under the point of view of safety analysis, STARDUST results show as dusts deposited inside divertor internal part, will not encounter a massive mobilization while, on the contrary, relevant movements are possible for dusts on VV bottom part.

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