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ASTEC simulations of dust resuspension in fusion containments compared with the “STARDUST” experimental data

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The ASTEC code is a system code originally designed to perform safety analysis in fission nuclear power plants and developed originally by IRSN (France) and GRS (Germany). Recently some modules of ASTEC have been modified by IRSN to be applicable for the safety analysis in the nuclear fusion plants. In particular the CPA module (thermal-hydraulics) and the SOPHAEROS module (aerosols and vapours transport, chemical reactions) have been updated to simulate dust resuspension phenomena in containments, such as the vacuum vessel and the neighbour volumes. It is possible to choose two different models: the “force balance” and the “rock’ and roll” model for which the particles are resuspended from the surface when they have gained sufficient vibration energy to escape from the adhesive potential well. To test the effectiveness of these models in the peculiar conditions existing in a Tokamak, simulations of dust resuspension have been carried on using the features and the data obtained from experiments performed in the past in the STARDUST (Small Tank for Aerosols Removal and Dust) facility, currently placed at the University of “Tor Vergata”. The final scope is to test the capability of the code to deal with the dusts resuspension phenomenon in near vacuum conditions. This facility is a small cylindrical vessel in which it is possible to simulate loss of vacuum accidents (LOVAs) at sub-atmospheric pressures pumping air from different valves. To support ASTEC calculations the ANSYS CFX code is applied to evaluate properly the flow field and the thermal-hydraulic parameters during the transient. The first results are encouraging but substantial modifications in the resuspension models are necessary to take in account the particular physical conditions such as the extremely low density and very high air velocities during the transient.

Key words: ASTEC, ANSYS CFX, STARDUST, Dust, LOCA, LOVA, Resuspension.

1. Introduction

A future DEMO fusion plant has the scope to demonstrate the capability to produce electricity by means of a fusion nuclear plantin which the fuel, i.e. tritium, is generated by the breeding material (i.e. LiPb or Li4SiO4). The plan is to build DEMO in Europe before 2050. Important topics to be investigated are those related to the safety of the plant. The deterministic analyses of the most important accidental events occurring in DEMO are the core of the safety assessment. The licensing process necessary for plant operation requests reliable simulation codes to analyze the abnormal transients. This paper focuses the attention on the improvements and validation of ASTEC code, originally designed for safety analysis in fission nuclear plants, to face the fusion accident analyses too. In particular the dust resuspension model in ASTEC has been deeply analyzed and modified to improve the ability of the code to simulate this physical phenomenon in the fusion frame that presents different conditions from the fission context. To validate the updated model the experimental data in case of a LOVA in the STARDUST facility [4] have been used. It is placed at the Rome University of “Tor Vergata“. The experimental set up is shortly described and the main results obtained with ASTEC calculations are discussed. The detailed calculations of the flow, the velocity field and friction velocity inside STARDUST have been done simulating the air ingress in the VV with ANSYS CFX code to make a comparison with ASTEC.

2. ASTEC code

ASTEC V2.1 code (Accident Source Term Evaluation Code) was jointly developed until 2015 by the “Institut de Radioprotection et de Sûreté Nucléaire” (IRSN, France) and the “Gesellschaft für Anlagen-und Reaktorsicherheit” (GRS, Germany), and from 2016 only by IRSN. Its capabilities have been recently extended by IRSN to address the main accident sequences which may occur in the fusion installations, in particular in ITER. Preliminary analysis of the physical and chemical phenomena involved in the accidents in the ITER installation [1] showed that most of the ASTEC models developed for Pressurized Water Reactors (PWRs) were already applicable in the fusion plant context such as thermal-hydraulics in the ITER large-size volumes after water or air ingress into the VV, two-phase thermal-hydraulics in the cooling circuits, dust transport and re-combiners of combustible gases (hydrogen, carbon monoxide). ASTEC “fusion” modelling includes resuspension, oxidation and impact of the dust on critical flow, jet impaction on walls, wall material oxidation (Be and W) and specific gas

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phase/walls thermal transfers. The new physical modules developed into ASTEC have been added at two specific modules suitable for the fusion scope: the CPA module that simulates thermal-hydraulics in containment and the SOPHAEROS module that simulates the transport of fission products such as vapours and aerosols in the PWR Reactor Cooling System and the containment.

2.1 ASTEC Mechanical Resuspension Models

In the ASTEC code as in the literature, are present mainly two type of mechanical resuspension models: the force balance model and the Rock'n Roll (R&R) model [2-3]. The first one consists in a "mechanical" approach, in which the particles are resuspended if the lift force due to the flow exceeds the forces of adhesion due to the interaction between the particles and the surface. With this approach clearly the resuspension is strongly dependent on the values of the forces. The R&R model instead considers not the forces but the momentum due to the aerodynamic forces and adhesion forces and in particular in this model the drag force plays a key role compared with the lift force. Besides in this model is considered the distribution of the momentum. The R&R model is more suitable for fusion scope, due to the limitations reported of the force balance approach in some experimental tests. For that it has been chosen also in [3] for its completeness and easy implementation in a SA (Safety Analysis) code. Based on the R&R model and four sets of experimental results [3] (STORM, Braaten, ORNL, Hall), Biasi established correlations defining the average value and the standard deviation of the distribution of the dimensionless adhesion forces according to the diameter of the particles. It is interesting to note that STORM and ORNL experiments were carried out for multi-layer deposits of particles of sizes equal or smaller than a micron-meter whereas Hall and Braaten experiments were carried out for a distributed full-range deposit and for larger sizes of particle (from 10 to 30 μm).

The very good agreement between the R&R model with Biasi correlations and the experimental results (STORM, Braaten, ORNL, Hall) obtained in the past is at the origin of the choice of this model to be implemented in the SOPHAEROS module of ASTEC [6].

3. STARDUST facility and dust resuspension experiments

For a fusion experimental device like ITER the dust resuspension is an important safety concern because the plasma disruptions and the bumps of the plasma against the first wall or the divertor (DV) cause significant erosion of materials [4]. The dust generated sticks on the VV internal surfaces and lays down mainly in the bottom of the VV, over and under the DV.

The scope of the STARDUST experiments was to build a base of knowledge about the dust resuspension in a heated volume at low pressure (5-100 Pa), simulating the conditions of the ITER VV, when a LOVA occurs. The facility (Fig. 1) is a stainless steel cylindrical tank on the bottom of which a tray containing dust is placed (at the divertor level).

In the VV tank the initial pressure was 5 Pa and the tank walls at 110 ◦C constant. An air inlet through valve A (case A), in the center of the tank lid representing the equatorial port of a VV, or through the valve B (case B), in the bottom of the tank lid, representing the divertor port in the VV, simulates a LOVA. Table 1 shows the test matrix used for this study.

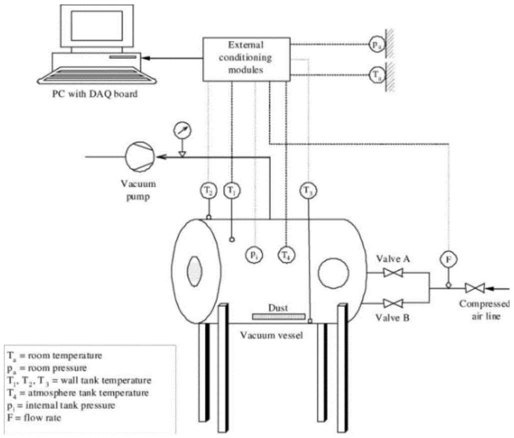

Figure 1. STARDUST facility layout

Table 1. Test matrix for the STARDUST experiments

Test	Dust	Inlet Position	Resuspension Rate Exp.(%)
W_b_300	Tungsten	B	1.6-10.3
SS_b_300	Stainless Steel	B	94.0-99.9
C_b_300	Carbon	B	99.9-100.0
W_a_300	Tungsten	A	0.03-0.07
SS_a_300	Stainless Steel	A	0.0003-0.007
C_a_300	Carbon	A	0.002-0.007

The pressurization rate used was 27 l/m for 300 Pa/s. The dust tray is weighted before and after the LOVA. The type of dust utilised (tungsten, carbon and stainless steel) is similar to that existing inside the VV of a fusion device. The dust grains have typical dimensions (<1 μm up to few tens of μ) of the powder found in the VV of the experimental fusion devices.

By means of a SEM [4] the mean dust diameter was measured: for carbon it was 4–5 μm, for tungsten 0.3–0.5 μm and for stainless steel 20–30 μm. 5,0 gr of tungsten, 4,5 gr of stainless steel and 1,8 gr of carbon have been used in the tests to comply with the tray dimensions.

4. ASTEC V2.1 simulations of the STARDUST experiments

To simulate the STARDUST experiments with ASTEC the CPA module is used for the thermal-hydraulics and aerosol behaviour in containment. In cascade the CPA outcomes are the inputs for SOPHAEROS to compute the transportation of aerosols (i.e. deposition, suspension and resuspension phenomena). The STARDUST nodalization in ASTEC (Fig. 2) is made by 9 internal volumes connected each other with atmospheric junctions and by heat structures to simulate the walls to reproduce the experimental conditions.

The walls are kept at a constant temperature of 110 °C. The air injection through the different valves is simulated by means of a fan reproducing the flow conditions measured by the flowmeter. The dust deposition has been simulated considering a dust injection before activating the fan. During this phase the air mass flow rate is zero.

The CPA outputs (volume temperature, volume carrier-fluid pressure, carrier-fluid component mass ratio for each species, carrier fluid mass flow rate in each volume, temperature for each heat structure) are supplied as inputs to SOPHAEROS, using the same nodalization [5].

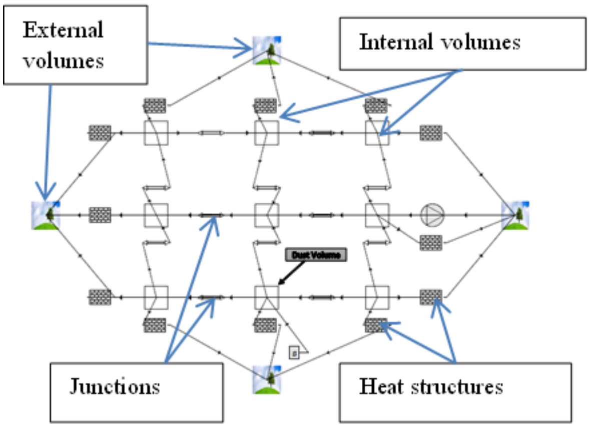

Figure 2: STARDUST nodalization for the case A

Due to the fact that with the Lumped-Parameter approach used in CPA it is a difficult task to calculate correctly the local thermal-hydraulic parameters, it was necessary to check the thermal hydraulic parameters of the volume in which the dust were deposited tuning the CPA user-dependent parameters (hydraulic diameter, local air mass flow rate) to obtain the velocity, the friction velocity and the thermal hydraulic parameters of the flow (density and kinematic viscosity) as far as possible in line with the ANSYS CFX simulations, as detailed in the next chapter. At this scope the mass-flow rate in ingress and in exit from the dust volume has been taken from the ANSYS CFX computation to compute the velocity in the dust volume (Fig.5 and Fig.7) .Then tuning the real hydraulic diameter corresponding to the real dimension of the dust volume has been possible to obtain the friction velocity in ASTEC (Fig 4. and Fig.6.).

5. ANSYS CFX simulations of the STARDUST experiments

The ANSYS CFX tool has been used to evaluate properly the thermal hydraulic parameters during the transient. It was necessary to calculate correctly the friction velocity for assessing the performance of the resuspension model with the peculiar conditions of a LOVA. ANSYS 17.0 has been adopted at this scope. Only the fluid domain has been taken in account because the walls are at constant temperature, then their influence are negligible. 100 Pa of initial pressure, reached in the experiments after 0.5 s, was a good compromise to avoid convergence issues. 368.15 K was fixed as initial temperature. As boundary condition the experimental mass flow rate in ingress is used. The pressurization in ANSYS, as in ASTEC, was perfectly coherent with the experimental results (Fig. 3).

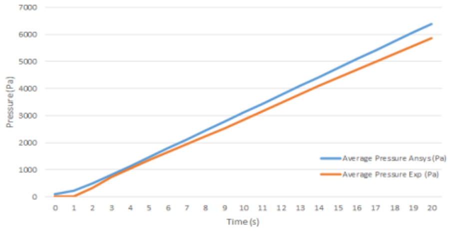

Figure 3. ANSYS vs Experimental Internal Pressure (case A)

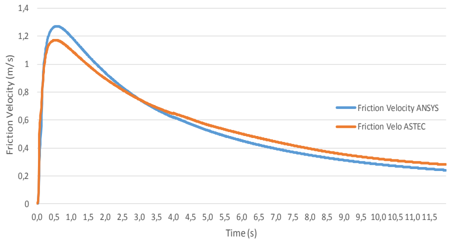

Figure 4. Friction Velocity-ANSYS vs ASTEC (case A)

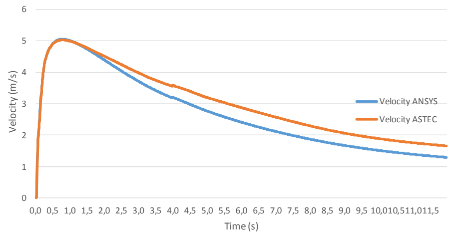

Figure 5. Average Velocity-ANSYS vs ASTEC (case A)

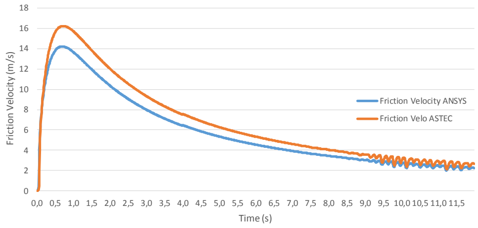

Figure 6. Friction Velocity-ANSYS vs ASTEC (case B)

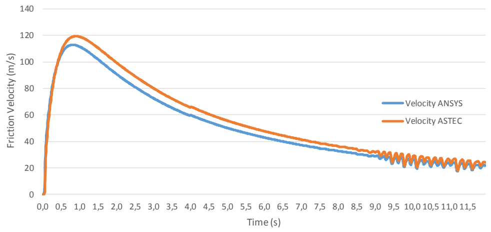

Figure 7. Average Velocity-ANSYS vs ASTEC (case B)

Besides, the ANSYS and ASTEC velocity and friction velocity calculated in the dust volume have been compared, obtaining a good agreement (Figs. 4, 5, 6 and 7) meaning that the tuning gave good results and that the expression for the velocity and friction velocity in ASTEC represent well this phenomenon.

Table 2 shows the comparison between experimental data and ASTEC resuspension rates.

Table 2: Test matrix for the ASTEC results

Test	Resuspension Rate ASTEC (%)	Resuspension Rate Exp. (%)
W_b_300	0.0000025	1.6-10.3
SS_b_300	92.67	94.0-99.9
C_b_300	26.92	99.9-100.0
W_a_300	0.0	0.03-0.07
SS_a_300	0.22	0.0003-0.007
C_a_300	~0.0	0.002-0.007

For the stainless steel (average diameter 20-30 μm), the code gives good results compared with the experimental ones. For cases B with smaller particles size (carbon and tungsten dust), an underestimation is observed.

For the case A, a slight underestimation is observed for carbon and tungsten while for the stainless steel there is an overestimation (0,01 g resuspended versus 0,00015 g in average).

This could be due to several aspects that influence the resuspension, in particular:

- the agglomeration of C and W grains, clearly visible but not quantifiable in the experiments, was not included in the ASTEC simulation.

- the adhesion forces have not been measured but applied those calculated with the Biasi correlations [3].

This could cause an overestimation, as for example pointed out in [8] for the tungsten dust.

The next step of ASTEC validation will test the effects on resuspension of the fluctuation distribution of the aerodynamic forces that in this model has been considered Gaussian The drag and lift forces expressions [6], [7] used in ASTEC need to be verified in sub-atmospheric pressure conditions.

6. Conclusions

The ASTEC validation versus STARDUST experimental data has been carried out to demonstrate the suitability of the code to be applied for LOVA analysis in which dust resuspension occurred. To support ASTEC calculations, ANSYS CFX was applied to evaluate properly the flow field and the thermal-hydraulic parameters during the transient. The two codes showed satisfactory agreement in the results.

The ASTEC resuspension rates relating to SS dust fits well with the experiments while there is an underestimation of smaller size dust (C and W) that has the tendency to agglomerate. The phenomenon has not been modelled in ASTEC in these tests.

The applicability of the resuspension model to the real conditions of a fusion power plant as ITER is not completely demonstrated in high vacuum conditions. Refinements and investigation are still necessary and they are going on.

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