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Full Length Article

Implementation and validation of a resuspension model in MELCOR 1.8.6 for fusion applications

Bruno Gonfiotti*, Sandro Paci

University of Pisa, Department of Civil and Industrial Engineering (DICI), Largo Lucio Lazzarino 1, 56126, Pisa, Italy

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ABSTRACT

In a fusion reactor, a continuous erosion of the Plasma Facing Surfaces (PFSs) occurs during normal plant operations. This erosion creates a particles debris (dust) spanning from 1 μm to 50 μm in dimension. These formed dust deposits on the bottom of the Vacuum Vessel (VV), i.e. on the divertor surface. In case of Beyond Design Basis Accident (BDBA), this dust may be mobilized and transported towards the confinement building, or even into the outer environment. Therefore, the evaluation of the maximum mobilized dust mass is a safety issue of main concern, because it may pose a radiological risk to plant operators and to the outer population. To investigate these incidental scenarios, lumped-parameters codes such MELCOR are commonly employed. A specific version of MELCOR, capable to treat the phenomena occurring in a fusion reactor, is developed by Idaho National Laboratory (INL). Although, a model to treat the mobilization of dust is still not yet implemented in this specific MELCOR version. This paper presents, after a review of the available resuspension models, the selection of a specific resuspension model and the efforts made for its validation against different experimental tests. The selected model is the semi-empirical "Force Balance" model, just implemented in the ASTEC and ECART codes, but specific modifications were introduced to allow its implementation in MELCOR through ad hoc developed Control Functions (CFs). Its validation shows a quite good agreement with most of the experimental tests investigated, highlighting its capabilities for the safety analysis of the forthcoming fusion reactors.

1. Introduction

During normal plant operations of a fusion plant, a continuous erosion of the Plasma Facing Surfaces (PFSs) occurs [1]. To reduce the severity of this erosion, these PFSs are commonly protected by mean of a protective layer. This layer reduces the erosion rates, but important quantities of dust can be still formed. This dust − having a size in the range of 1–50 μm [2] – may pose a radiological hazard to the plant staff and the outer environment in case of a Loss of Vacuum Accident (LOVA) or an In-vessel Loss Of Coolant Accident (LOCA). Indeed, this dust may mobilize (resuspend) and relocate into the VV Protection System (VVPS) or into the confinement building, or event into the outer environment in case of a major accident [3].

Major accidents in fusion reactors – called Beyond Design Basis Accidents (BDBA) – are commonly investigated employing lumped-parameter codes, such as the specific MELCOR code versions [4,5]. These specific versions were developed basing on their Light Water Reactors (LWRs) counterpart, but additional models were introduced to cope with the specific phenomena occurring in fusion reactors. In a previous MELCOR version (1.8.5) – not publicly available – different dust mobilization models were implemented [6], but these models weren't reintroduced in the latest released MELCOR 1.8.6 version [5]. Thus, the goal of the present paper is to describe the efforts did for the introduction and the validation of a resuspension model in this latest MELCOR 1.8.6 fusion version. This model was introduced to give conservative evaluations of the resuspended mass under the most different flow conditions possible.

The semi-empirical Force Balance model – originally implemented in ECART [7] and ASTEC [8] codes – was selected for its implementation in MELCOR 1.8.6 [9]. Minor modifications were introduced to the original ECART model to avoid iterative calculations within each time-step. The particles distribution is subdivided into different groups, each characterized by a mean diameter. For each group, the adhesive and aerodynamic forces are calculated at each time-step based on the surrounding carrier fluid conditions. The adhesive forces hold the dust particles on the surface, while the aerodynamic ones trigger the movement of the particles. When the aerodynamic forces exceed the adhesive ones, the particles of the considered group are mobilized.

The article is subdivided into two main sections: the first one

* Corresponding author.
E-mail addresses: bruno.gonfiotti@for.unipi.it (B. Gonfiotti), Sandro.paci@ing.unipi.it (S. Paci).

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describes the theory and the equations behind the employed resuspension model, and the second describes the performed validation activities. A conclusive section is also reported, highlighting the future perspectives for the evolution of the model itself.

2. Aerosol resuspension models

Different numerical models were proposed in the latest years to predict aerosol resuspension rates during an incident [10,11]. Such models can be subdivided into two main categories: the "force balance" and the "energy balance" models. In the force balance models, the dust particles mobilization/resuspension occurs if the aerodynamic forces exceed the adhesive ones. The ECART force balance model [10], and the MELCOR v2.2 lift-off model [12] are clear examples of these "force balance models". In turn, the resuspension occurs if enough energy is transferred to the particles by the motion of the surrounding flow in the energy balance models. The Rock'n'Roll model [11] and its following improvements [13–15] are examples of these energy balance models.

Most of these resuspension models were created looking at typical LWRs primary system conditions [16–18], and only few of them have been validated for application to fusion reactors [19,20]. Among these models, the ECART one was one of the most extensively applied to fusion installations [7]. Compared to other resuspension models, the ECART one is less sophisticated, but it is able to roughly consider all the main phenomena occurring in the resuspension process. Thanks to its simplicity and capabilities on fusion related scenarios, this model was selected for the present implementation in MELCOR 1.8.6.

2.1. The implemented force balance model

The model considers the aerosol particles population subdivided into groups, each characterized by a mean diameter (or radius). For each given aerosol group, the adhesive ($F_A(r)$) and the aerodynamic forces ($F_R(r)$) are calculated at each time-step according to the local thermal-hydraulics conditions. Resuspension occurs if the resultant force ($F(r)$) – expressed as the difference between the adhesive and the aerodynamic forces – exceeds zero. The number of particles of a given aerosol group re-suspending each second [1/s] – also called the "resuspension rate" – is calculated according to Eq. (1):

$$\begin{cases} \Lambda(r) = 0.4037[F(r)]^{0.6003} & 0 < F(r) < 3.065\cdot10^{-4}\ \mu\mathrm{N} \\ \Lambda(r) = 90.28[F(r)]^{1.269} & F(r) \geq 3.065\cdot10^{-4}\ \mu\mathrm{N} \end{cases} \quad (1)$$

These two functions were fitted considering the resuspension rates measured in several tests performed in the ART, PARESS T10, and STORM experimental campaigns [9] (Fig. 1).

2.1.1. Adhesive forces

Considering two particles, P_1 and P_2, deposited on a surface with a given roughness ε, the forces that hold them attached to the surfaces are (Fig. 2): the gravitational force ($F_{A,g}$), the cohesive force ($F_{A,c}$), and the friction adhesive force ($F_{A,f}$). The gravitational force (Eq. (2)) is predominant for particles larger than 100 μm, while it becomes almost negligible for particles smaller than 10–50 μm.

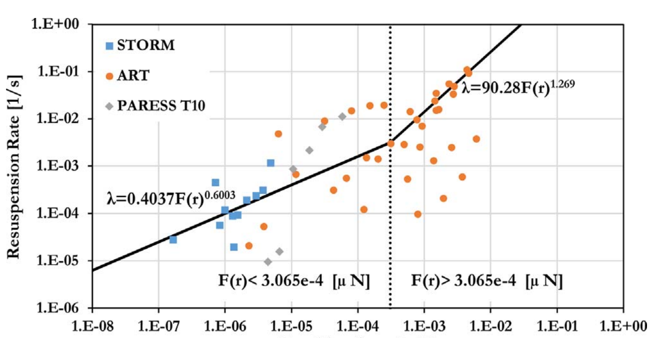

Fig. 1. Fitting function vs resuspension rates measured in the ART, PARESS T10, and STORM experimental campaigns.

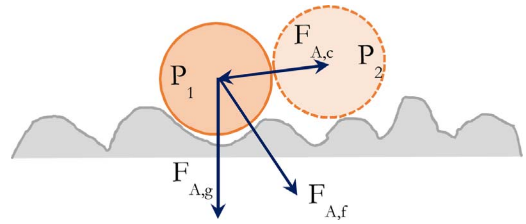

Fig. 2. Adhesive forces.

$$F_{A,g} = \frac{4\pi r_p^3}{3}\rho_p g \quad (2)$$

Gravitational force.

Where r_p is the particle radius, r_p the particle density, and g the gravitational acceleration.

The cohesive force is caused by the intermolecular attraction (Eq. (3)).

$$F_{A,c} = 2Hr_p\gamma \quad (3)$$

Cohesive force.

Where H is an empirical coefficient and γ the collision shape factor. The empirical coefficient H mediates the cohesive force according to the number of layers of deposited particles. In the original ECART model [9], H is computed according to the number of layers, while in MELCOR a constant value of $10e^{-6}$ N/m was assumed. A value of $10e^{-6}$ N/m means that no less than 10 layers of deposited particles are present at the beginning of the calculation. The collision shape factor describes the increased effective collision cross-section compared to the mass-equivalent sphere. If γ is set to 1 the particle is considered a perfect sphere.

The frictional adhesive force is due to the sliding and the rolling resistances (Eq. (4)), and it is calculated as a combination of the gravitational and of the cohesive forces [9].

$$F_{A,f} = 0.2(F_{A,g}\gamma^3 + F_{A,c}) \quad (4)$$

Frictional adhesive force.

2.1.2. Aerodynamic forces

Considering a particle fully submerged in the laminar sublayer formed by the flow of a carrier gas/liquid, the aerodynamic forces triggering its mobilization are two (Fig. 3): the drag force ($F_{R,d}$) and the burst force ($F_{R,b}$). The drag force is due to the carrier fluid motion inside the laminar sub-layer (Eq. (5)).

$$F_{R,d} = \tau_0\pi r_p^2\chi^{2/3} \quad (5)$$

Drag force.

Where τ_0 is the shear stress at the wall, and χ the aerodynamic shape factor (assumed equal to 1). The aerodynamic shape factor accounts for the different resistance to motion of the actual particle if compared to the mass-equivalent sphere. If $\chi = 1$ the particle is considered as a perfect sphere. The shear stress at the wall is calculated according to Eq. (6).

$$\tau_0 = 0.125\lambda\rho_g v_f^2 \quad (6)$$

Shear stress at the wall.

Where r_g is the fluid density, v_f the flow velocity of the carrier gas, and λ the flow resistance coefficient. In ECART, this flow coefficient (λ) for rough walls is computed through the implicit Colebrook's equation (Eq. (7)). Implicit equations can't be solved with the approach employed to implement the resuspension model in MELCOR, thus an explicit correlation was used. The Haaland's approximation (Eq. (8)) is an explicit correlation [21] characterized by a very simple form and with a