NENE
International Conference
Nuclear Energy for New Europe

Sensitivity Analyses by a CFD Model on Water-Wall Behaviour in a LW SMR during SBO conditions

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ABSTRACT

In the present paper, previously obtained CFD results concerning the behaviour of water-walls introduced for passive cooling of containment systems of Small Modular Reactors (SMRs) are extended by sensitivity analyses. The targeted scenario concerns Station Black-Out (SBO) conditions, in which the decay heat is transferred from the inner containment shell surface to the pool of the water-wall system. The work has been performed in the frame of the EU ELSMOR Project, having as main objective to design methods and tools for stakeholders to assess and verify Light Water Small Modular Reactor (LW SMR) safety when these reactors will be installed across Europe.

The performed sensitivity analyses focus on the representation of turbulence and on the consequent heat diffusion in the water pool, by considering different turbulence models and numerical advancement schemes. A simplified model set up making use of the CATHARE 3 system code is also used to assess the overall observed behaviour. The additional knowledge of the addressed phenomena obtained by these new analyses allows drawing further conclusions on the behaviour of containments equipped with water-wall systems, to be adopted in European SMRs presently under development.

1 INTRODUCTION

Small Modular Reactors (SMRs) are presently among the most relevant subjects of research in the field of innovative nuclear reactors, for the perspective to complement large scale reactors in key areas for the decarbonisation of the energy sector. For instance, the coupling with renewable energy sources in hybrid energy systems and the capability to replace old fossil fuelled plants are two of the main addressed topics. The characteristics of SMRs as safe and flexible plants to support the energy transition are therefore presently investigated with renewed impulse, in a lively innovation environment in which IAEA has recently recognised several tens of different concepts being proposed worldwide [1].

The European scenario, in particular, is showing a new interest for the characteristics of SMRs and important political decisions are being taken at the national and the European Union levels. In this frame, a remarkable step was taken on April 4th 2023 with an ambitious Declaration on ‘EU Small Modular Reactors (SMRs) 2030: Research & Innovation, Education & Training’ signed by Commissioner Mariya Gabriel and EU nuclear stakeholders, namely Nucleareurope, the Sustainable Nuclear Energy Technology Platform (SNETP), the European Nuclear Society (ENS) and the European Nuclear Education Network (ENEN) [2]. The declaration suggests that the European Union is committed “to lead research, innovation, education and training for the safety of European SMRs in support of the EU pre-partnership on SMRs”.

As a forerunner in this innovative scenario, the EU ELSMOR Project (Towards European Licencing of Small Modular Reactors) seeks to design methods and tools for stakeholders to assess and verify Light Water Small Modular Reactor (LW SMR) safety when installed across Europe [3]. In this frame, collection and dissemination of data on LW SMRs is among the actions performed in the project. In particular, in Work Package No. 4 of the project analysis, methods and tools for the safety demonstration of improved or innovative containment safety features of integral SMRs have been developed and assessed. Furthermore, in Work Package no. 5 safety methodologies developed in the project are applied to the E-SMR with reference to specific accident scenarios, as the loss of the normal cooling system.

In the frame of a doctoral research on design and safety aspects of SMRs for the energy sector decarbonisation in Europe, a contribution has been given to the ELSMOR project. The past contribution regarded the behaviour of containment pools adopted as water-wall systems for rejecting the decay heat in case of postulated accidents, assessed by numerical analyses. In particular, in a recently published archival paper, water-wall was considered by addressing available experimental data and variously scaled systems modelled by CFD tools, in order to extrapolate the behaviour observed in small-scale facilities to the full-scale reactor size [4]. Since studying the full size of the reactor containment easily results in unaffordable CFD problems even for RANS techniques, the methodology adopted in the work consisted in using both 2D and 3D geometries, addressing different scales and carefully comparing the obtained results to judge about their scalability. In addition, a simplified model of the pool obtained by the CATHARE 3 system code [5] was used to compare the overall behaviour obtained by a lumped parameter representation of the pool with detailed CFD calculations.

In the present paper, the previously obtained results are extended by a further sensitivity analysis concerning the representation of turbulence in the water pool, also addressing a Station Black-Out (SBO) scenario with different turbulence models and numerical advancement schemes. CATHARE 3 is again used to assess the observed behaviour with the mentioned simplified but reliable model. The additional knowledge of the addressed phenomena obtained by these new analyses allows drawing more sound conclusions on the behaviour of containments equipped with water-wall systems, to be adopted in European SMRs presently under development.

2 CFD MODEL AND SIMPLIFIED LUMPED PARAMETER MODEL

The code used to perform the RANS analyses is STAR-CCM+ (version 16.06) [6], whereas for the lumped parameter model the thermal-hydraulic code CATHARE 3 V2.1.0 [5] was adopted. For the sake of completeness, in this section the main characteristics of the CFD and the lumped parameter models are described, though suggesting the reader to refer to the above-mentioned work (i.e., [4]) for a more in depth overview. In both cases, 72 hours of reactor time after SBO occurrence were simulated, which is the characteristic time span a passive safety system is expected to handle a long term accident scenario without any external energy source [1].

2.1 CFD model

RANS analyses were performed by using a 2D axisymmetric domain, defined by preserving the water pool volume and assuming axial symmetry of the external containment system (see [4] for details). In the previous work the obtained results achieved with 3D calculations showed great similarity to what was achieved with the 2D analyses [4], making the latter the most attractive solution to perform repeated sensitivity analyses. The adopted mesh, partly shown in Figure 1 together with all the boundaries of the computational domain, is a polyhedral one with base a size of 8 cm, selected for making affordable the calculations in terms of computational resources. The mesh refinement close to the containment wall and to the pool external concrete wall was made by adopting a 20 cm thick prism layer, which contains 9 nodes with a stretching factor of 1.25. Owing to the large scale of the system, there is no pretence to be completely accurate in describing the details of the flow close to the surface, reverting to a high Reynolds number (i.e., “high y+”) treatment.

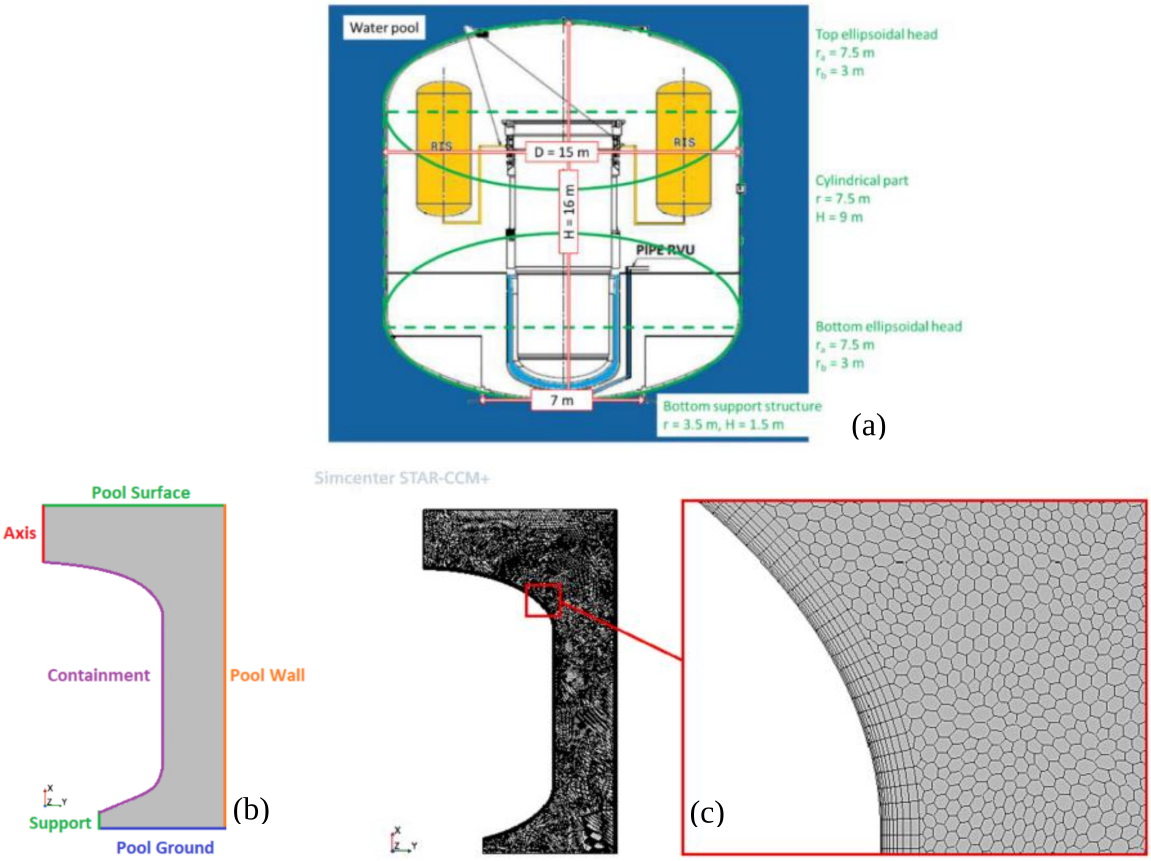

Figure 1: Computational domain with a sketch of the modelled system (a), the boundaries (b) and a portion of the generated mesh adopted in the CFD analyses (c) [4].

Concerning the boundary conditions, referring to Figure 1 where the name of each boundary is shown, they are the following: 1) the *Axis* surface is the symmetry axis of the domain, hence an “axis” condition was imposed on it; 2) the *Support* and *Pool Ground* surfaces were set as adiabatic walls; 3) On the *Pool Wall* surface heat losses were imposed by means of a convective boundary condition, thus imposing the convective thermal resistance equal to the conductive one (please refer to [4] for more details); 4) the *Pool Surface* was treated as wall with no-slip viscous condition (i.e., no shear stress induced on the flow), simulating the free surface. Moreover, to account for the evaporative heat losses, again a convective boundary condition was imposed with a convective heat transfer coefficient evaluated by using the heat and mass transfer analogy under certain simplifying hypotheses [4] (see, e.g., [7] or

[8]). The latter procedure, indeed, allowed to obtain a heat transfer coefficient dependent on the temperature of the pool free surface; 5) on the *Containment* boundary the decay heat power was imposed, whose curve was taken from the ANS-94 + 2σ standard considering only U-235 as reactor fuel [9], then extrapolated in the frame of the ELSMOR project [3] up to 10^6 seconds. The boundary condition was imposed by performing a fitting of the discrete values provided by the ELSMOR database, obtaining the following time behaviour of the decay power

$$\dot{Q}(t) = [1 - \varphi(t, 1000)] \cdot f_1(t) + \varphi(t, 1000) \cdot f_2(t) \quad (1)$$

where

$$f_1(t) = -3.693 \ln(t) + 37.088 \quad (2)$$

$$f_2(t) = 125.74 \cdot t^{-0.321} \quad (3)$$

and $\varphi(t, \gamma)$ a smoothing function defined as

$$\varphi(t, \gamma) = \frac{1}{2}\left[1 - \arctan\left(\frac{2000 - t}{\gamma}\right)\right] \quad (4)$$

Figure 2 shows the decay curve with the results of the interpolation procedure.

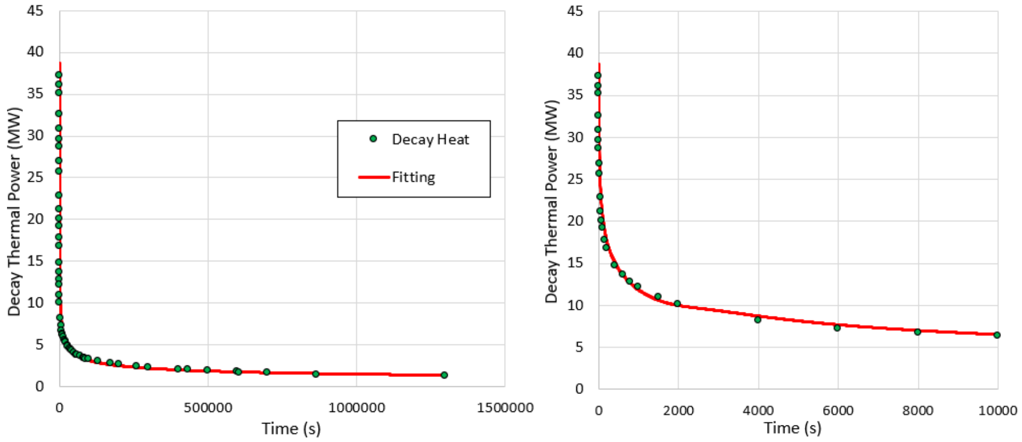

Figure 2: Decay heat power curve and its fitting imposed as boundary condition to perform the CFD analyses [4].

Unlike the previous work [4] where only a Standard k-ε model was adopted, in this frame different turbulence models were used to perform the calculations, in order to conduct a sensitivity analysis on turbulence representation.
In particular, the following turbulence models were used to perform the simulations:

- Standard k-ε model [10] with a two-layer "all-y+" wall treatment;
- Realizable k-ε model [11] with a two-layer "all-y+" wall treatment;
- SST k-ω model [12] with a "high-y+" wall treatment;
- Reynolds Stress Transport (RST) model with a two-layer linear-pressure strain model [13].

Moreover, also a Standard k-ε model with a second-order time discretisation was used, in order to check for the possible effect of numerical diffusion on the results.

2.2 Lumped parameter model

In order to obtain a simple estimate of the overall behaviour of the cooling pool a 0D model was adopted by using the CATHARE 3 code V 2.1.0 [5]. The lumped parameter model consists of a 30 m tall 0D VOLUME domain simulating the pool and the upper space over it. To simulate the latter, non-condensable gases (i.e., air) were assumed to be present in the atmosphere. The containment wall was constructed with a shape similar to that adopted in the CFD simulations by means of truncated cones. The free surface of the pool (i.e., the interface between the pool and the upper environment) was simulated by using a break on the upper part of the domain, which was voided before the beginning of the transient analysis until the requested level of 20 m was reached. Also in this case, the decay heat curve taken from the ELSMOR database was imposed as heat source in the containment wall.

3 OBTAINED RESULTS

After simulating 72 hours of physical time with the two models described in the previous section, hereafter the results of the analyses are briefly described. Concerning the temperature evolution of the cooling pool, Figure 3 shows the temperature fields achieved in the water-wall after 25 hours of simulating time with the four different turbulence models. The analysis with the Reynolds Stress Tensor transport model was conducted only up to 30 hours of physical time since it required much more computational effort. Nevertheless, 30 hours resulted a time span long enough to highlight the differences achieved with respect to the other turbulence models. Concerning the vertical velocity field, its comparison is shown in Figure 4.

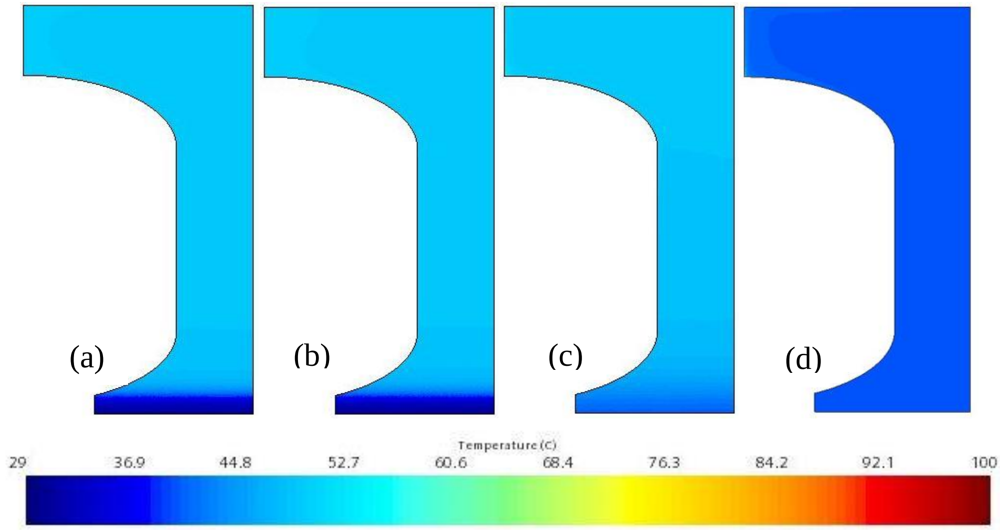

Figure 3: temperature field achieved in the cooling pool after 25 hours of simulating time with different turbulence models: (a) Standard k- ε; (b) Realizable k- ε; (c) SST k- ω; (d) RST transport model.

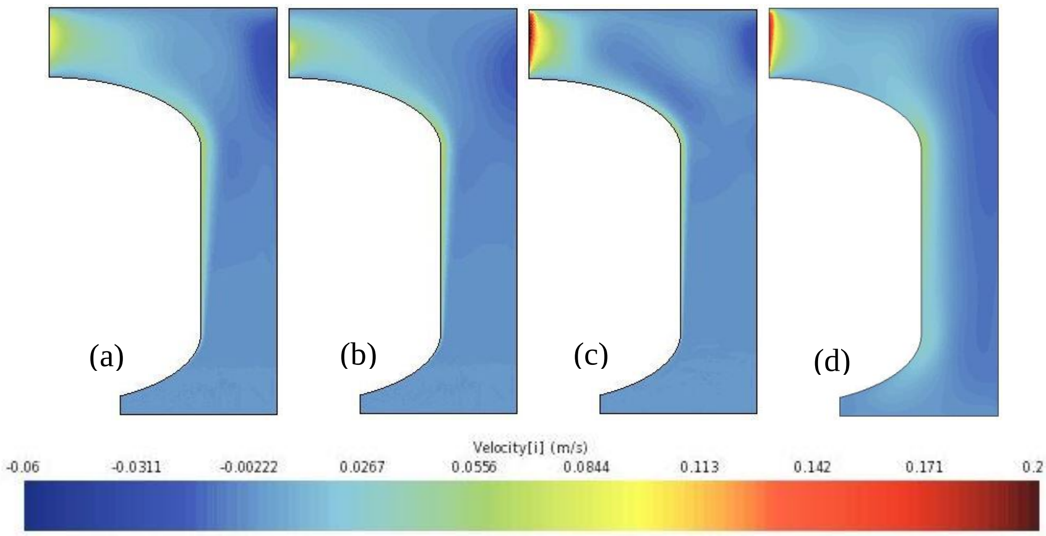

Figure 4: vertical velocity field (in m/s) achieved in the cooling pool after 25 hours of simulating time with different turbulence models: (a) Standard k- ε; (b) Realizable k- ε; (c) SST k- ω; (d) RST transport model.

As it can be noted from Figure 3, the temperature in the water-wall was found to be very uniform along the vertical direction (i.e., along the heated part of the containment), meaning that only a mild thermal stratification was achieved during the transients. This phenomenon, already noted in the previous work [4], might be due to the particular boundary conditions imposed on the surfaces (i.e., heating from the containment and cooling from the upper surface and concrete wall), which led to have, in the long term, a well-mixed condition inside the pool. Moreover, the use of k-ε turbulence models led to have a "cool floor" of water on the bottom side of the pool, which can be explained with the fact that in that section of the pool there is no heating of the water. Nevertheless, the thermal stratification achieved in the bottom part of the pool was found to be definitely milder when the SST k-ω model was used to perform the analysis. The latter result shows an increase in the overall diffusivity of the CFD representation when that particular turbulence model is used. Another interesting difference achieved is related to the RST model. In this case, the thermal stratification almost disappears along the vertical direction of the pool, leading to have a more uniform temperature distribution also at the bottom of the water-wall. The latter result may be again related to a higher diffusivity of the model with respect to the other ones and to a different velocity field simulated by the code as shown in

Figure 4.

In addition, as it can be seen from

Figure 4, the flow is found to detach from the containment surface in correspondence of the lower edge of the upper dome, something already noted also in the previous work [4]. It is interesting to note that the vertical velocity field achieved by using k-ε turbulence models is found to be very similar. However, the SST k-ω model resulted in higher vertical velocities in the upper plume compared with the ones from the k-ε models, something that could be considered responsible of the better-mixed condition in the pool and, consequently, of the lower thermal stratification.

To give a better overview of the results, Figure 5 shows the behaviour of temperature achieved on a vertical section of the pool, built to be at mid distance from the pool wall and the vertical portion of the containment. The latter results give also the idea of what was achieved with the Standard k-ε model adopting a second-order time discretization, being very similar to the cases where a first order Euler-type time discretization was used.

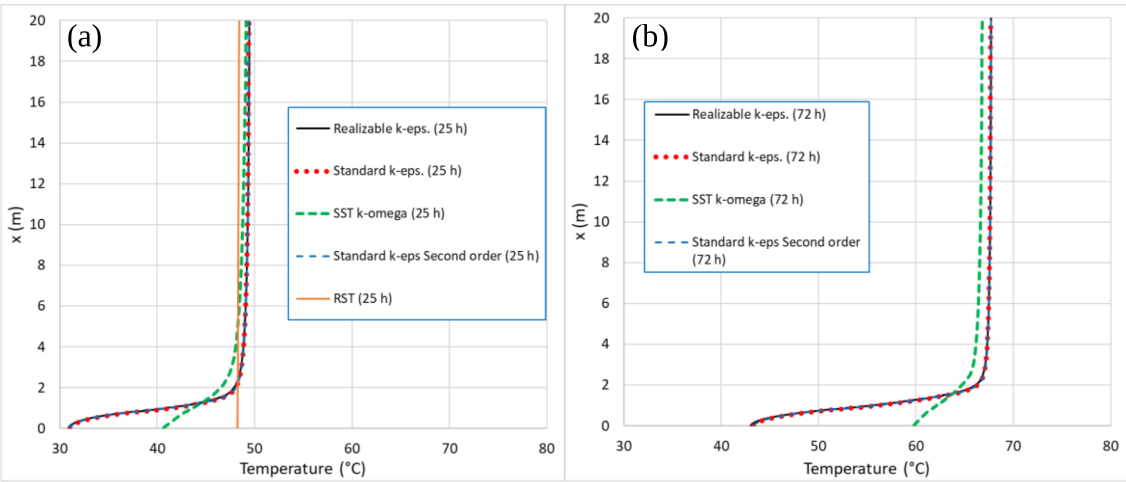

Figure 5: temperature behaviour along a vertical section of the pool achieved with different turbulence models at two reactor times: (a) 25 h; (b) 72 h.

Finally, concerning the calculations carried out with the thermal-hydraulic system code CATHARE-3, Figure 6 shows the comparison between the average water-wall temperature achieved with CATHARE-3 (the variable LIQTEMP is shown) and that achieved with the CFD analyses. To obtain a meaningful comparison between the lumped parameter model used in

CATHARE-3 and the CFD results, the mass averaged temperature obtained by the CFD code was used.

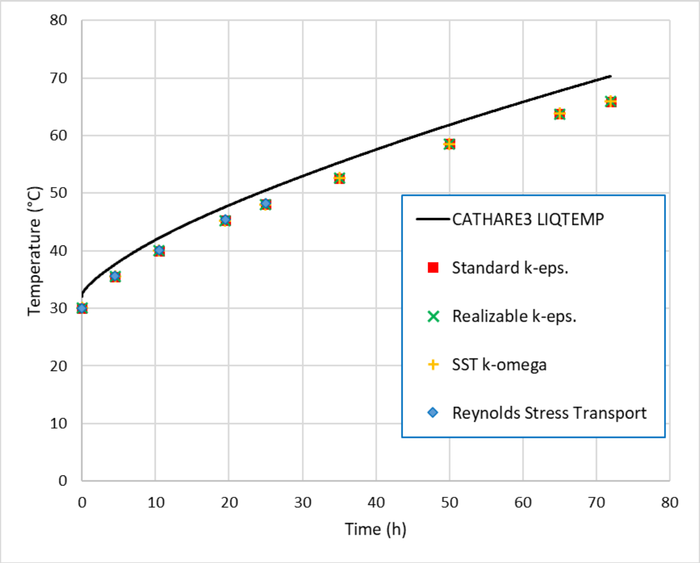

Figure 6: Comparison between CFD mass averaged temperature and CATHARE3 results.

As it can be seen from Figure 6, the behaviour of the water-wall temperature achieved by the two codes is quite similar also from a quantitative point of view, providing reasonable assurance about the correctness of the order of magnitude of the achieved results in terms of temperature.

4 CONCLUSIONS

The results obtained in these analyses on the behaviour of the water-pool during the postulated release of decay heat from the containment show some interesting features, summarised below.

- From a global point of view, the pool during the 72 hours of the transient keeps an appreciable margin to saturation, showing a sufficient capacity to absorb the released heat without reaching bulk boiling. Though local nucleate boiling could be possible, depending on the actual distribution of the power along the containment wall, here assumed uniform, a grace period of 72 hour seems to be confirmed with consistent margins.
- No matter slight differences, all the CFD models and the two different adopted transient numerical schemes predict very similar behaviour of the water pool and, interestingly enough, all suggest a high degree of uniformity of temperature along the pool height corresponding to the heated region.
- The differences observed in the behaviour of the k-ε models, on one side, and of the SST k-ω and the RST models, on the other, are mostly related to the possible presence of a layer of cold water in the unheated part of the pool, at the bottom of the containment. While k-ε models predict the existence of a quite stable stratification, the two other models, though at different extents, suggest a greater degree of mixing, much higher in the case of the Reynolds Stress Transport model.
- The latter detail, as already mentioned, does not change the conclusions that can be reached at this level of approximation about the involvement of a quite large part of the water of the pool to the heat transfer process, which is even higher in the case of the k-ω model and of the RST model.

The latter conclusion should be discussed considering a possibly uneven distribution of the power released by the containment to the pool, to be made based on the actual scenarios assumed to occur inside the containment, something that could not be considered at the present level of approximation.

ACKNOWLEDGEMENTS

This project has received funding from the Euratom research and training programme 2014-2018 under Grant Agreement No. 847553. The cooperation of Dr. Nils Reinke from GRS (Germany) in defining the boundary conditions of an Academic Exercise addressed in Work Package 4 of the ELSMOR Project and in providing information for computing the here addressed SBO scenario is gratefully acknowledged. The research work of Ing. Alessandro De Angelis was supported by the Ministry of University and Research (MUR) as part of the PON 2014-2020 "Research and Innovation" resources – Green/ Innovation Action – DM MUR 1061/2022.

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