Thermal analysis of HI-STORM 100S dry cask with the MELCOR code

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Abstract. As spent nuclear fuel (SNF) pools are reaching their capacity, dry storage systems have been introduced worldwide as interim step before permanent deep underground disposal. Thermal behaviour of the SNF, and of the system containing it, has proven to be essential to ensure fuel rod integrity for the entire storage time. In the effort to achieve a proper characterization, this work investigates the capabilities of the lumped parameter MELCOR 2.2 code to model the thermal evolution of SNF in the scenario of a concrete-based dry cask. Being dry storage systems completely outside MELCOR domain of application, a number of approximations and hypotheses have been necessary, without however jeopardizing the real cask characteristics and behaviour. Results have been discussed to be coherent with what physically expected and verified against estimates previously obtained from a FLUENT calculation on the same system. The code shows the ability to well predict the Peak Cladding Temperature (PCT) and its location, as well as temperature radial profile; however, some discrepancies show up when analysing temperature profiles in the down-comer and in the air gap. For this reason, further assessment studies should be performed to confirm the potential shown in this preliminary work.

1. Introduction

Since the advent of nuclear energy, the safe management of spent nuclear fuel has been recognized as an important and inevitable step in the back-end of the fuel cycle. With the repositories for the final disposal still not ready and the spent fuel pool reaching their maximum capacity, the dry cask option has increasingly spread all over the world as interim storage for up to 100 years.

Regardless of the design choices of different producers, dry casks show a number of characteristics that make their demand (and employment) constantly increasing: passivity, flexibility, modularity, and above all the fulfillment of the safety requirements as stated in US NRC regulations [1]. In this regard, having to guarantee the fuel rod integrity and being most degradation mechanisms temperature-dependent, the thermal analysis of the spent fuel has been identified as high-priority [2].

The majority of the past work on the thermal environment of the cask systems has been conducted with simulations, with only few in-situ tests performed. Initially, thermal analyses were carried out for certification purposes [3], showing therefore a strong conservativism. In the 80s, thermal-hydraulic computer codes based on finite volume methods (as COBRA-SFS) were employed (as in [4] and [5]). However, the uncertainties, mainly due to the over-simplification of energy and momentum equations, weakened the accuracy of the results.
Nowadays, the higher fuel burnup (up to 50 GWday/t) and the necessity to have a bigger fuel capability inside a dry cask require to design better performing casks and, as a consequence, to perform new updated thermal analyses. Computational Fluid Dynamics (CFD) 3D codes have been employed for the purpose ([6], [7], [8], [9], [10] and [11]). Notwithstanding the ability of CFD codes to gather the thermal behaviour of a dry storage system, experimental data are limited, making a thorough validation difficult to implement. Moreover, despite the improvements, the computational cost is still very high.

In this paper, the lumped parameter MELCOR 2.2 code [12][13], which is not a pure thermal-hydraulic code, but rather an engineering software developed to model the progression of severe accidents in nuclear power plants, has been employed to conduct a thermal study of the HI-STORM 100S dry cask [8] under steady-state conditions. The results have been then compared to the data previously obtained in an independent FLUENT calculation [9], with main focus on the Peak Cladding Temperature (PCT), which has been taken as a reference in US NRC regulation in many regards affecting the SNF integrity.

2. System description
The system addressed in this work is the HI-STORM (Holtec International Storage and Transport Operation Reinforced Model) 100S version B: being one of the most utilized among dry casks around the world, it is well representative of its category and all the phenomena involved in its operating conditions. It consists of a sealed metallic Multi-Purpose Canister (MPC) – backfilled with high-purity Helium and vertically loaded with spent fuel – placed inside a concrete overpack, as shown in figure 1.

![Figure 1. HI-STORM 100S components: (from left to right) concrete overpack, metallic MPC, honeycomb and fuel.](image)

The system is designed to be in fully compliance with the requirements of 10CFR72 [1], as explained in its Final Safety Analysis Report (FSAR) [8], which also thoroughly reports all the main data and information for each component.

In substance, the HI-STORM 100S dry cask relies on the thermosiphon effect of the Helium inside the canister and on the natural circulation of air to meet the thermal acceptance criteria stated in [14], that is to maintain the fuel cladding temperature below 673 K for normal condition of storage (843 K for off-normal and accidental conditions). In addition, its structure and design are intended to also provide confinement, radiation shielding and criticality control in an autonomous way.

3. MELCOR model
Despite the number of models and packages available in the MELCOR 2.2 code ([13] and [14]), no “ad hoc” intrinsic model addressing directly a dry cask system is present. As a consequence, a set of hypotheses and approximations have been adopted in the following analysis, in order to adapt the code to a new application field:
• Uniform axial heat distribution has been considered;
• Fuel assemblies have been considered equally powered;
• Insertion channel in the down-comer have been ignored (conservative choice);
• Bottom/top plug and spacer grids have not been modelled;
• Lower plates are required by the code, but they do not exist in the real cask.

The adoption of two different spatial nodalizations has been necessary: one, required by the COR package, to model the thermal response of the stored fuel, and one representing the thermal-hydraulic meshing (CVH and FL code packages) for the two gas regions (internal to the canister and the external air channel).

The discretization required by COR involves the creation of cells deriving from the subdivision of the “core” (representing the spent fuel zone) in radial rings and axial levels, as shown in figure 2 and figure 3. Four radial rings are present: the first three rings containing respectively 4, 12 and 16 fuel assemblies, and the fourth one simulating the He down-comer. In turn, 12 axial levels are employed to represent, from bottom to top, lower plenum, lower plates, fuel active length and upper plenum. The number of axial levels and radial rings is a compromise between geometry of the system, code requirements and desired level of detail.

Figure 2. Radial nodalization.

Figure 3. Axial nodalization.
To simulate the Helium atmosphere inside the canister, 24 Control Volumes (CVs) and 26 Flow Paths (FLs) have been employed (figure 4). Initially, the CVs has been assumed to be in non-equilibrium conditions at 0.334 MPa and 294.26 K, whereas FLs have been addressed through appropriate parameters to correctly describe the flow direction, the available flow area, and the pressure drops characteristic of each flow path. Frictional pressure drops have been represented by means of the single-phase friction factor $f$, defined as $f = S_{lam}/Re$, where $S_{lam}$ is the laminar friction coefficient. The $S_{lam}$ default value of 16.0 is appropriate for circular tubes, but not for bundles, so a $S_{lam}$ of 32.0 [15] has been set for the FLs inside the honeycomb. As for the form-losses contribution, the applied K factors for forward and reverse flow have been extrapolated from [16], in which the hydraulic characterization of a PWR fuel assembly in low Reynold number flows is illustrated.

CVH and FL packages have also been employed to define the air channel between the canister and the overpack: 8 volumes, initially at 0.101 MPa and 300 K, connected by 7 vertical flow paths have been used for the purpose, as shown in figure 5. In addition, 2 FLs have been added to represent the entry and exit of the air. Since the real cask presents 4 inlet and 4 outlet, real opening areas and lengths have been carefully taken into account to preserve as much as possible the total mass flow rate.
The walls of both canister and cask have been modeled by 14 and 11 Heat Structures (HSs) respectively, using the HS package. In this context, key parameters have been set for both convective and radiative heat transfer. Given the main role of the heat exchange from He to air, characteristic lengths for the canister HSs have been imposed equal to their thickness. As for the radiative heat transfer, instead, the structure-to-structure radiation model has been employed to take into account the exchange between the honeycomb and the canister, and between the canister and the cask. Since the considered surfaces face each other and the distance between them is very small, view factors have been chosen as 1.0, thus maximizing the surface-to-surface exchange. In parallel, emissivities for both carbon and stainless steel have been user-imposed, as well as the conductivity of the concrete.

As for the fuel, 32 standard PWR 17x17 fuel assemblies have been considered, and modeled as if equally powered and with a uniform axial heat distribution. The DCH package has been then activated to impose a total decay heat power equal to 30.0 kW in the active zone of the fuel assemblies.

On the practical side, the described nodalization is also the result of a study apt to reduce the computational time. By running some preliminary calculations, the complexity of the CVH meshing and the activation of advanced code options have been identified among the main reasons for calculation slow advancement. Accordingly, too small volumes have been collapsed into bigger ones, without however undermine the result precision.

4. Results

As already said, the MELCOR 2.2 capability to investigate the behaviour of the HI-STORM 100S system under steady state conditions has been investigated in this work. Furthermore, MELCOR results have been compared with those deriving from a previous FLUENT 14.0 calculation [9].

The Peak Cladding Temperature (PCT), being the parameter under regulatory surveillance, has been chosen as the main target variable of the analysis. Predictions from MELCOR and FLUENT are reported in table 1.

| PCT (K) | Axial Position (m) |
|---------|-------------------|
| MELCOR  | 631.35            |
| FLUENT  | 628.1             |

Table 1. MELCOR-FLUENT comparison - PCT.

MELCOR and FLUENT well agree on both the maximum value of the cladding temperature and on its location, with very little differences. The small relative deviation of the PCTs (less than 1% if considering that the initial temperature is around 300 K) is quite likely within the uncertainty bands of both types of tools. Besides, the location calculated by FLUENT corresponds almost exactly to the middle-point of the axial level determined by MELCOR, that is where the temperature is calculated. In essence, both codes locate the PCT in the upper part of the inner fuel assemblies, consistently with what physically expected, and they both predict a temperature more than 40 K below regulation limits for the scenario. An outstanding agreement is also shown in figure 6, where the radial thermal profiles at the PCT axial location are compared.

There is a substantial correspondence between MELCOR and FLUENT in the fuel zone. A certain amount of discrepancy is instead present in the temperature values related to the down-comer and the air channel. Given the quite different approaches (with FLUENT having a “quasi-continuous” profile, and MELCOR showing an average temperature within each CV), these mild differences could be still considered acceptable. On top of this, the predicted temperatures in the air channel become further closer if a weighted average is applied to the data provided by FLUENT according with its meshing.

Figure 7 shows the results of this average process at z=4.22 m.
Figure 6. Temperature radial profile at PCT axial location.

Figure 7. Air channel temperature at z=4.22 m.

Extending this averaging procedure to different axial locations in the air channel, a comparison between the temperature axial profiles in the channel has been possible. As displayed in figure 8, the two codes show a similar trend, but MELCOR overpredicts the air temperatures with a maximum ΔT of about 15 K along the gap. The reasons behind this MELCOR behaviour are still being studied, but, given that the He profile in the down-comer (figure 9) does not support the thesis of an heat “over-transfer” from the fuel to the air, the oversimplification of the channel inlets and outlets (leading to a worse air distribution in the channel) could be involved.

Figure 8. Air channel temperature profile.
Finally, in order to have a deeper understanding of the cask behaviour, its fluid dynamics has also been investigated. Despite being a lumped parameter code and not solving the complete momentum equation, MELCOR shows velocities of the same order of magnitude as FLUENT. This makes the differences in figure 10 completely acceptable.

5. Conclusions
The main objective of this work was to assess the capabilities of the MELCOR 2.2 code to predict the performance of a dry storage system. Being MELCOR a lumped parameter code developed to model the progression of severe accidents in Light Water Reactors (LWRs), the analysis of a dry cask is completely outside its natural domain of application. As a consequence, a number of hypotheses and approximations have been necessary for the creation of this first-of-a-kind input deck.

The models implemented in MELCOR have been capable to represent the general behaviour of the addressed system: all parameters under regulatory surveillance could be determined by the code, together with other variables useful to have a broader idea of the physical phenomena involved in the system operation.

By performing some preliminary runs, the meshing (and its complexity) have been identified as one of the reasons for slow calculations. Therefore, simplifying the nodalization plays a fundamental role when trying to save computational time but still maintaining a certain level of accuracy in the results.

In short, MELCOR has proven to be a useful tool in the thermal analysis and it has exhibited good ability and flexibility in adapting itself to systems completely different from standard nuclear reactors. The consistency with reality shown in the results is remarkable in this “extended environment”.
However, notwithstanding the promising predisposition revealed by the code, additional studies have to be carried out in order to deeper investigate some deviations shown in the results respect to CFD analysis and to make firmer conclusions.

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