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Thermal modeling of SNF behavior during dry storage: From 3D CFD to simple approaches

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ABSTRACT

A full thermal modeling of dry casks is presently manageable through 3D thermo-fluid dynamic analytical tools and a good progress has been achieved worldwide. A thorough validation, though, is still an open issue. In this sense, a meaningful international collaboration is ongoing under the frame of the ESCP program. Understanding of the thermo-fluid dynamics of SNF dry storage casks may support the development and/or use of fast tools that provide nearly immediate estimates of meaningful variables, like the cladding peak temperature. This paper is an overview of the work done by CIEMAT along both paths, part of it in collaboration with University of Pisa (UNIPI). Through the present manuscript, examples of both approaches are given.

1 INTRODUCTION

The safe storage of Spent Nuclear Fuel (SNF) in dry conditions previous to its final disposal in a deep geological repository should meet a number of regulatory requirements. One of them is keeping its structural integrity. In the case of in-cask dry storage, a number of phenomena might jeopardize the fulfilment of this requirement, from cladding creep to embrittlement due to the radial precipitation of hydrogen absorbed by cladding during the irradiation in the reactor. These mechanisms are strongly affected by the cladding thermal state, which has been shown in the criteria to be met to guarantee cladding integrity: in fact, temperature limits for the cladding have been set at 673 K and at 843 K for normal conditions and off-normal conditions, respectively. In other words, an effective SNF cooling should be ensured, which emphasizes the importance of a suitable modeling of dry cask thermal performance. In the last decade, the enhancement of computational fluid-dynamics (CFD) capabilities allowed a 3D modeling of dry cask systems, and numerous investigations have explored different approaches in the application of CFD tools.

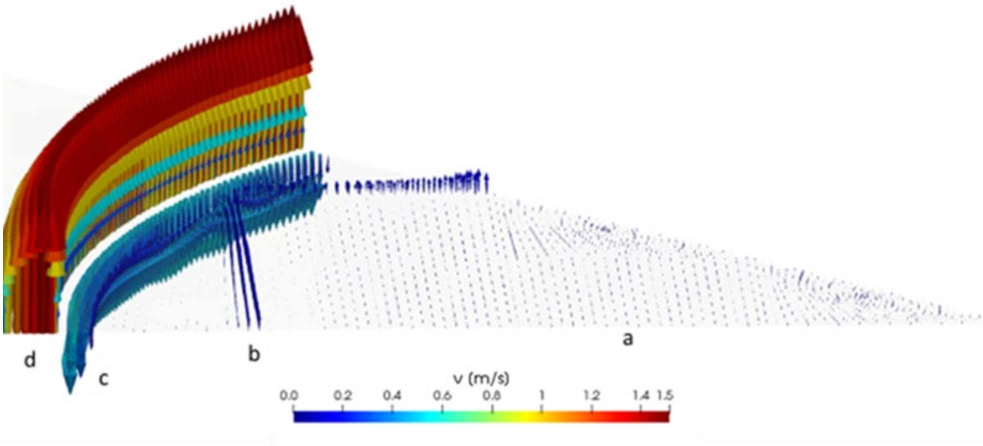
2 THE 3D CFD APPROACH

The present contribution is an overview of CIEMAT's experience in the thermal modeling of dry casks, from the fundamentals of the approximations made when using 3D CFD to alternative simple methods used to calculate peak clad temperatures. The verification of the 3D approach was done through the modeling of the HI-STORM 100 concrete cask under normal conditions and its comparison against a previous work reported by Holtec International [1]. An excerpt of it may be seen in Table 1; at the time, CIEMAT used the FLUENT 14.0 software. Figure 1 shows some of the insights gained through these simulations in terms of fluid motion inside the Multi-Purpose Canister (MPC), where He circulated in the laminar regime (Re ~ 400) setting Bernard-Rayleigh vortexes at the upper plenum of the canister, and in the natural circulation air channel, in which air gets accelerated within the interval of the transition regime (Re_{max} ~ 6000). A discussion of the major challenges faced and the hypotheses made is to be included [2].

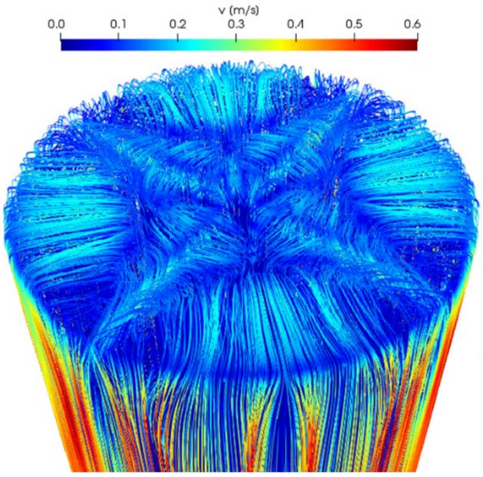
Table 1: Verification of 3D modeling of dry casks.

	Holtec	CIEMAT	Relative Deviation (%)
Maximum Temperature (K)			
Fuel	650.35	649.58	-0.22
Basket	648.65	647.91	-0.21
MPC shell	515.92	522.76	3.17
Average Temperature (K)			
Lid bottom plate	423.15	419.03	-3.35
Air outlet	385.92	382.18	-4.35

One of the major challenges for the 3D modeling is validation. There are very few data considered 3D-graded and most of them are confidential. Under the frame of the ESCP (Extended Storage Collaboration Program) led by EPRI (Electric Power Research Institute of USA), Sandia National Laboratories (SNL) conducted experiments in a scaled-down, heavily instrumented facility to mimic thermal-fluid dynamics in a vertical concrete cask. CIEMAT modeled those experiments by using a geometrical simplification of fuel assemblies in the FLUENT 18.0 and found qualitative and quantitative consistencies with measurements [3]. Figure 2 shows the predictions relative error for the cases of high pressure and high power, and low pressure and low power; as noted, the only noticeable deviations occurred at the lower part of the experimental set-up in the high power and pressure test.



(a) Gas velocity profile (radial):
He around the fuel (a,b); He in the downcomer (c);
Air in the annular gap between MPC and external cask (d).



(b) He streamlines within the MPC

Figure 1. 3D results of a concrete dry cask

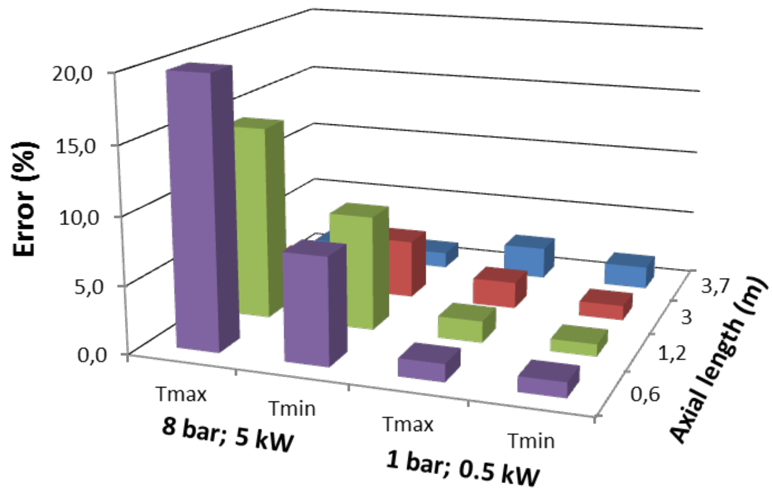


Figure 2. Predictions relative errors for the SNL tests

In addition, two alternative methodologies to CFD calculations to address the thermal characterization of the canister under off-nominal conditions will be described for the case of a He-leaking canister, which would be a challenging thermal scenario as it would result in the degradation of heat transfer within the system [4]. Based on different approaches (i.e., control transfer functions and correlation between CFD-calculated steady state temperature with decay heat and internal pressure assuming slow pressure transient), they both provided comparable results and allowed drawing meaningful insights into the scenario, like the time to reach the thermal threshold (673 K) or the maximum decay heat below which such a threshold would not be ever reached.

3 THE SIMPLE APPROACH

Finally, simple approaches to calculate maximum temperature within the cask have been attempted [5], [6]. This might provide a fast tool to get estimates and, although it is still a work in progress, the first results look promising. In Figure 3 a reasonable accuracy is displayed when comparing MELCOR 2.2 (lumped parameter code developed in the field of severe accidents) estimates to those obtained with FLUENT under steady state of a concrete cask.

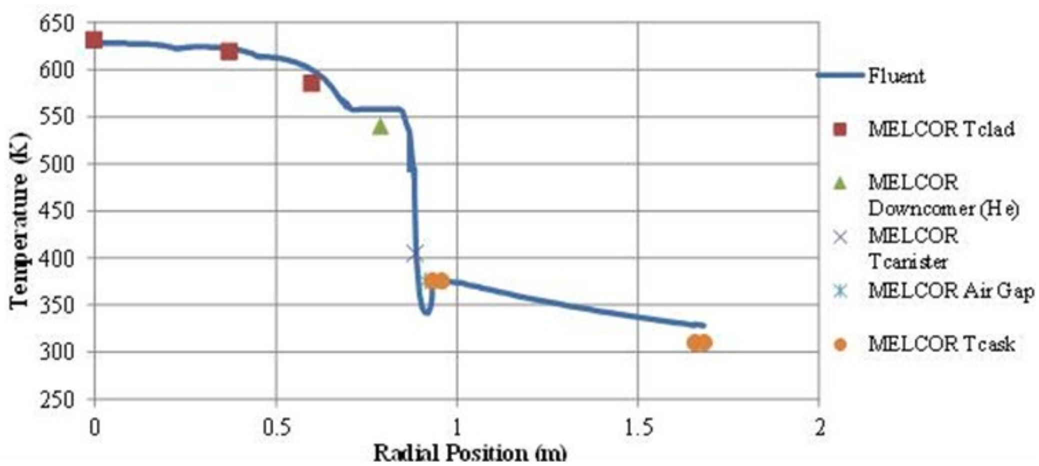


Figure 3. Radial thermal profile at the hottest position.

4 SUMMARY

In the previous sections, a few specific examples, based on CIEMAT's and UNIPI's experience, have been given to illustrate that a full thermal modeling of dry casks is presently manageable through 3D thermo-fluid dynamic analytical tools and a good progress has been achieved worldwide. A thorough validation, though, is still an open issue. In this sense, a meaningful international collaboration is ongoing under the frame of the ESCP program. Understanding of the thermo-fluid dynamics of SNF dry storage casks may support the development and/or use of fast tools that provide nearly immediate estimates of meaningful variables, like the cladding peak temperature.

REFERENCES

[1] HOLTEC International, "Final Safety Analysis Report (FSAR) for the HI-STORM 100 Cask System", 2010.

[2] L. E. Herranz, J. Penalva, and F. Feria, "CFD analysis of a cask for spent fuel dry storage: Model fundamentals and sensitivity studies", Ann. Nucl. Energy, vol. 76, pp. 54–62, 2015, doi: 10.1016/j.anucene.2014.09.032.

[3] L. Herranz *et al.*, "Validation of concrete dry cask models for BWR spent fuel.", 45 Reunion Anual de la SNE, 2019.

[4] J. Penalva, F. Feria, and L. E. Herranz, "Thermal performance of a concrete cask: Methodology to model helium leakage from the steel canister", Ann. Nucl. Energy, vol. 108, pp. 229–238, 2017, doi: 10.1016/j.anucene.2017.04.049.

[5] J. Penalva, F. Feria, and L. E. Herranz, "Modeling maximum fuel temperature in dry storage: From the CFD analysis to the engineering approach", Nucl. Eng. Des., vol. 383, no. May, p. 111435, 2021, doi: 10.1016/j.nucengdes.2021.111435.

[6] M. Angelucci, L. E. Herranz, and S. Paci, "Thermal analysis of HI-STORM 100S dry cask with the MELCOR code", J. Phys. Conf. Ser., vol. 1868, no. 1, 2021, doi: 10.1088/1742-6596/1868/1/012001.