Validation of CFD-methods for the calculation of the safe heat removal from the storage hall H of ZWILAG with temperature measurements

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ABSTRACT

In order to update the storing strategy in hall H of ZWILAG and include new storage cask types, the safe heat removal is verified with numerical analysis (computational fluid dynamics, CFD). The heat removal from the storage hall with large openings for the in- and outflow takes place mostly by free convection. The method, on which the numerical calculations are based, is validated with measured temperatures. This method comprises the use of the CFD-program ANSYS®-FLUENT [1] as well as specifications for the model of the storage hall and the casks (fuel assembly or high active waste), of the model parameters, of the essential fluid-mechanical parameters (buoyancy, turbulence, fins, etc.) and of the settings for the CFD-solver. The CFD-calculations results are in good accordance with the measurements. This validation can be used in the future, if operators of spent fuel assemblies and high active waste interim storage facilities need to store more casks than initially planned, or casks with higher decay heat loads. This demonstration would make it possible, from the thermal point of view, to use the existing storage hall rather than to build expensive structural extensions.

INTRODUCTION

In order to update the storing strategy in hall H of ZWILAG and include new storage cask types, the safe heat removal is verified with numerical analysis (computational fluid dynamics, CFD) using the CFD-program ANSYS®-FLUENT [1]. For this update, it is generally useful to examine the functionality of the passive heat removal during storage metrologically:

- Examine the global flow inside the storage hall with air temperatures and the conditions for heat removal at the casks.
- Confirm the used calculation method including the CFD-model, model parameters, essential fluid-mechanical parameters (buoyancy, turbulence, fins, etc.) and CFD-solver-settings.
- Demonstrate safety margins of CFD-calculation results.

Therefore, the method, on which the numerical calculations are based, is validated with measured temperatures. For this, the temperatures of the surfaces of the casks and the storage hall structures as well as the ambient air around the casks inside the storage hall and the air outside the storage hall have been measured.

The results of the extensive temperature measurements, which have been performed by using a thermography camera and thermocouples in January 2020 in the storage hall H of ZWILAG, will be presented. For the validation the measurement results for a chosen CASTOR® HAW 20/28 CG with a decay heat of about 28 kW are evaluated in detail.

The cask is chosen due to its high heat power and cask surface temperature in comparison to other finned casks in the storage hall. For a representative segment of the storage hall, CFD-calculations are performed based on the storage configuration, the heat loads of neighbouring casks and ambient conditions on the date of the measurements.

PASSIVE HEAT REMOVAL FROM THE STORAGE HALL

The heat removal from the casks in the storage hall H of ZWILAG is purely passive without the use of active cooling systems. The decay heat load of the inventories is transferred through the inventory and the basket to the cask cavity wall. From there the heat is conducted to the outer cask surface. The heat from the outer cask surface (most cask types have fins at the outer surface) is transferred mainly by free convection to the air in the storage hall and by thermal radiation to colder surfaces inside the storage hall (concrete structures or colder neighbouring casks).

Due to the temperature rise of the air at the hot surfaces of the casks and the storage hall walls in conjunction with the associated density change, a buoyancy flow results under the influence of gravity. With the resulting lower pressure cold air flows through the inlet openings in the storage hall walls into the storage hall, heats up and leaves the storage hall through the outlet openings in the ceiling of the storage hall, see Figure 1.

The predominant part of the released decay heat of the inventories is removed by convection with the air mass flow through the outlet openings to the ambient of the storage hall. Beside the heat removal by free convection and thermal radiation, a small amount of the decay heat is removed at the bottom surface via thermal conduction to the storage hall floor.

Dependant on the weather, an additional heat entry results from absorbed insolation at the outer surfaces of the storage hall. Further, wind can increase the heat removal from the outer surfaces of the storage hall.

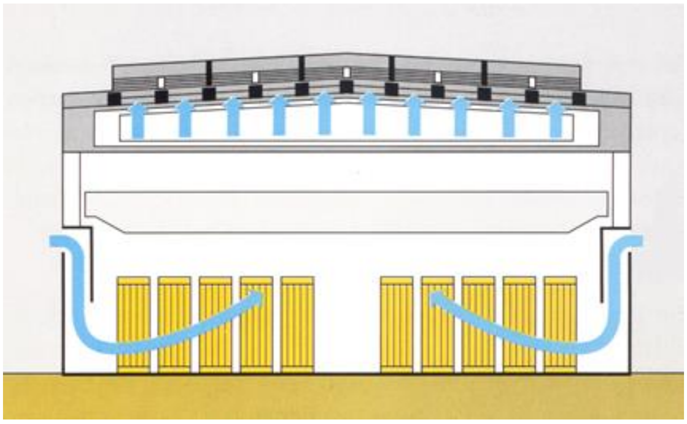

Figure 1: Passive heat removal – airflow (blue arrows) through the storage hall

VALIDATION METHODOLOGY

For the validation, a segment of the storage hall is chosen based on the cask allocation in the storage hall on the date of the measurement, the decay heat powers of the casks in the segment and the ambient conditions. This segment consists of a 5 x 5 pattern of casks and is used for the CFD-calculation in combination with the CFD-method of the thermal design of the storage hall. For the cask chosen for the measurements, more favourable ambient conditions – i.e. lower temperatures for the surfaces of the neighbouring casks and the storage hall structures – in comparison to reality are applied, so that the heat removal by thermal radiation is increased in the CFD-calculation, conservatively.

MEASUREMENTS IN ZWILAG IN JANUARY 2020

In January 2020 extensive measurements concerning the heat removal from the storage hall have been performed. During this, the temperatures of the air and the cask surfaces in the different hall segments with casks arranged in transverse and longitudinal rows have been measured and the flow conditions of the air have been evaluated. For the comparison of the results of the measurements and CFD-calculation, the results of one cask at position SP 130 are used.

The airflow around the casks in the storage hall has been examined qualitatively with smoke rods. This examination shows a strong transverse flow after the inlet openings in occupied storage hall segments and even around single positioned casks. The smoke even reaches the space between the fins, flows around the cask circumferentially and leaves the fins behind the cask in the main direction of the airflow. Due to the circumferential flow, a high heat transfer results leading to low temperatures at the outer cask surface at the front side of the cask directed to the inlet openings. This occurs especially for casks in longitudinal row LR-1 (see Figure 2). The heat transfer law for turbulent, free convection at a freestanding, vertical cylinder according to [2] used in the thermal design of the storage casks thereby leads to an underestimation of the convective heat transfer. In the frame of the comparison of the results, the positive effect of the transverse flow is shown in the CFD-calculations, too.

The ambient air temperature outside of the storage hall has been measured for two days before the measurement date. The temperatures of the outer cask surfaces follow the mean value of the ambient air averaged over the last two days and not the current air temperature or fluctuations during the day. On this basis, a mean value of the ambient air temperature of -1.8 °C is used in the steady state CFD-calculations for the temperature of the inlet air.

STORAGE HALL SEGMENT AND CFD-MODEL

Analogously to the calculations for the thermal design of the storage hall ZWILAG, a segment of the storage hall with 5 x 5 casks is considered for the calculations of the validation, where the segment around position SP 130 is chosen. Figure 2 shows the CFD-model with the cask at SP 130 (27.5 kW) including the 10 neighbouring casks with their decay heat powers during the measurement date. The cask allocation is identical to the allocation in reality inside the storage hall. Additionally, a part of the longitudinal wall with the air inlet wall and the inlet opening, the ceiling construction (dormer, outlet openings, ceiling binder) and the storage hall floor are part of the CFD-model.

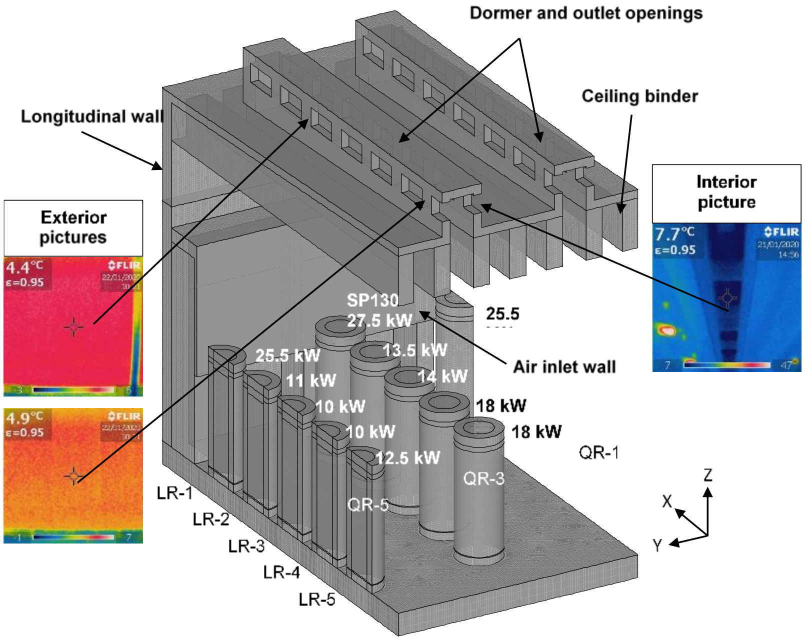

Figure 2: CFD-model of a segment of the storage hall and measured temperatures near the outlet openings

The total decay heat load of the storage segment amounts to about 138.5 kW. As the XZ-symmetry areas halve the casks in QR-5 and QR-1, the decay heat powers of these casks is halved, as well. For simplification, a constant heat load of 13 kW is used for the casks in the rear rows in LR-2 to LR-5. Therefore, the total decay heat load in the segment amounts to 131.2 kW, so that slightly lower temperatures in the casks result.

For the calculations the same model parameters and assumptions are used as for the calculations of the thermal design of the storage hall ZWILAG. The models of the casks in the CFD-model correspond to the models used for the thermal design of the casks in storage conditions.

The calculation mesh consists of about 5.5 million finite volumes (hexahedrons) with 5 million nodes and is generated with ANSYS® Mechanical APDL [3]. In the near-wall regions, a fine boundary mesh –

especially around the casks – is used to accurately predict heat transfer coefficients. The control volume is discretised fine enough to ensure dimensionless wall distances of about y+ = 11 to y+ = 60 according to [4], see Figure 3 (mean value about y+ = 30). The most accurate calculation of heat transfer coefficients is achieved by ensuring values of y+ ~ 30. A variation calculation with a 5-times coarser mesh shows higher values of y+ = 60 to 280 (mean y+ = 170) accordingly, which results to a 2 K lower maximum temperature at the outer cask surface of the hottest cask, which is still 2 K higher than the maximum measured temperature.

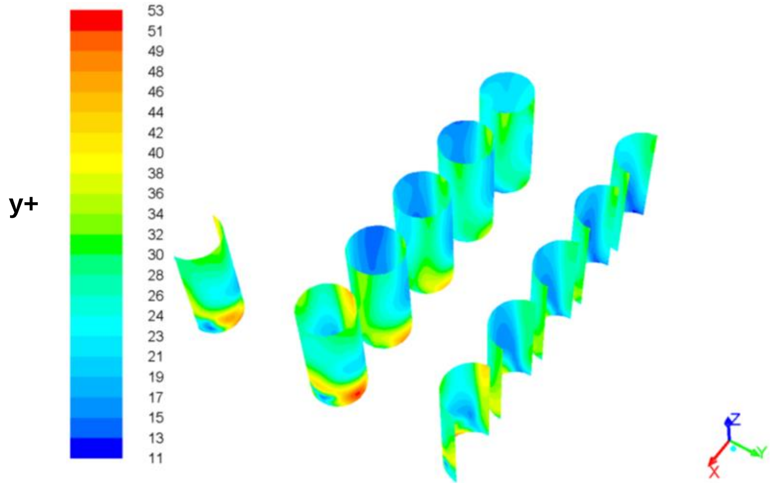

Figure 3: Dimensionless wall distance y+

COMPARISON OF THE RESULTS

Figure 2 shows the measured temperatures near the outlet openings at the in- and outside of the storage hall at SP 130. Table 1 shows essential results of the CFD-calculation and the temperature measurements. The calculated and measured temperatures at the outer cask surfaces are shown on Figure 4. Figure 5 shows the airflow on the segment.

The measured temperatures at the interior of the outlet openings amount up to 8 °C and show the effect of the thermal radiation from the casks (slightly higher temperatures). The measured temperatures at the exterior of the outlet openings amount up to 5 °C and show the effect of convection and thermal radiation to the ambient (slightly lower temperatures). For the outlet temperature of the air, a mean temperature of the solid structures at the outlet openings of (8 °C + 5 °C)/2 = 6.5 °C is reasonable, which coincides well with the calculated mean temperature of 7 °C.

The calculated air mass flow amounts to 14.5 kg/s with a convective heat removal of 130 kW (about 99 % of the total heat power). An analytical calculation based on the measurements shows an air mass flow of about 16.2 kg/s (10 % underestimation by the CFD-calculation). Despite the lower total decay heat power of 131.2 kW of the segment in the CFD-calculation in comparison to 138.5 kW in reality, a higher outlet temperature of the air and a lower mass flow of the air is yielded, which results from the conservative consideration of the segment in the CFD-model.

Table 1: Comparison of the results: CFD-calculation and measurements

Temperatures in °C	**CFD-calculation, T_{CFD}**	**Measurement, $T_{Meas.}$**	**Difference, $T_{CFD} - T_{Meas.}$**
Outer cask surface SP 130 (maximum)	48.5	44.6	4 K
Outer cask surface SP 130 (finned zone, mean)	39	~ 37	2 K
Outer cask surface neighbouring casks LR-1 (finned zone, mean)	30	~ 35	-5 K
Outer cask surface neighbouring casks LR-2 to LR-5 (finned zone, mean)	24	~ 29	-5 K
Inlet wall (mean)	8	~ 10	-2 K
Floor between cask rows	5 – 9	7 – 12	-2.5 K
Inlet air (mean)	-1.8	-1,8	0 K
Outlet air	7.0	6.5	0.5 K

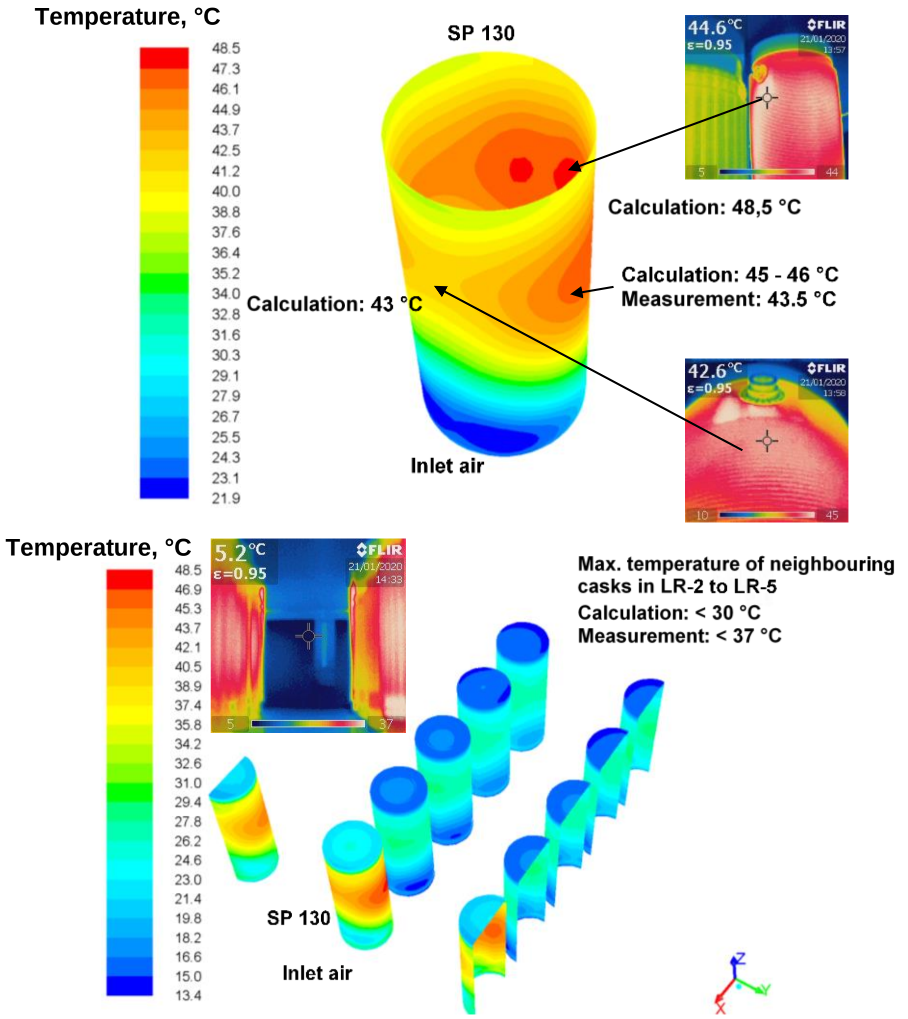

Figure 4: Comparison of the temperatures at the outer cask surfaces in the segment

The maximum outer surface temperature of the cask at SP 130 (Figure 4) is located at the leeward side of the cask and amounts to 44.6 °C (measured) and 48.5 °C (calculated), so that the calculation conservatively overestimates the temperature by 4 K. The overall temperature distribution as well as the maximum and minimum values are in good accordance. The temperature at the outer surfaces of the neighbouring casks and the storage hall structures (Figure 4) are in good accordance, too. The temperature difference amounts to 2 K to 5 K, where the calculation shows a general underestimation, which is conservative with respect to the validation methodology.

The neighbouring casks in LR-2 to LR-5 effect the heat removal of the front casks in LR-1 in two ways:

- The temperatures of the outer surfaces of the rear casks are higher than the temperatures of the storage hall structures, which reduces the heat removal by thermal radiation of the casks at LR-1.
- Due to the heat load of the rear casks the air mass flow and the convective heat removal of the casks at LR-1 are increased.

To show the effect of the rear casks, a variation calculation with only three casks in LR-1 without the rear casks in LR-2 top LR-5 is performed (total heat load of 53 kW in the modelled segment). In total, a mass flow of air of about 10.5 kg/s is calculated compared to an analytically calculated mass flow of air based on the measurements of about 11 kg/s (5 % underestimation by the CFD-calculation). Due to lower cask temperatures of the variation calculation in comparison to the basis calculation, the increased heat removal by thermal radiation overcompensates the decreased convective heat removal.

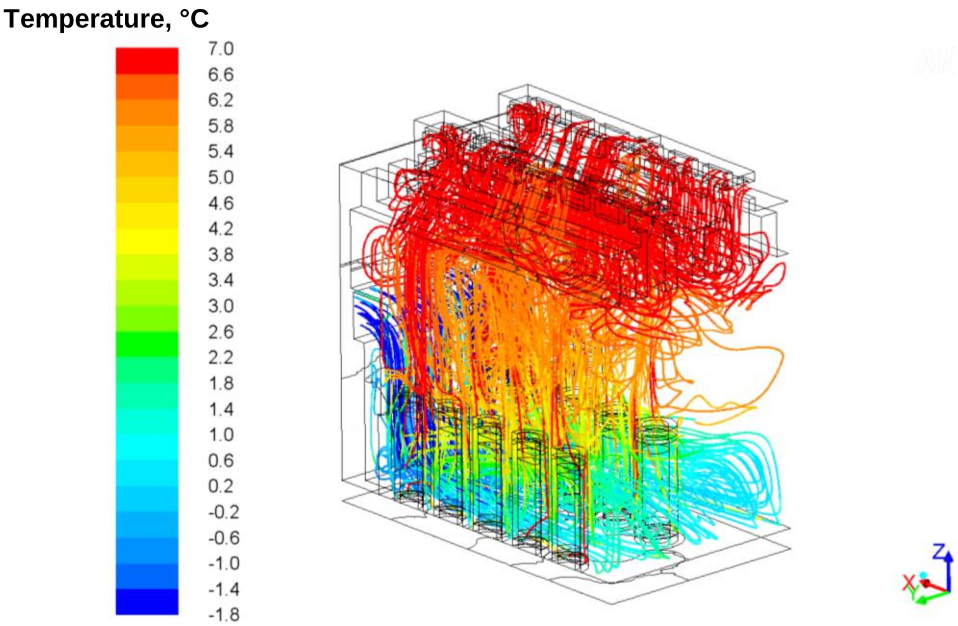

Figure 5: Air flow in the segment

CONCLUSIONS

The comparison of the measurements and the results of the CFD-calculations show a good accordance of the global flow in the storage hall (air mass flow and the outlet temperature of the air). The air mass flow is slightly underestimated, so that a conservatively high outlet air temperature is calculated. The temperatures at the outer surface of the chosen cask at SP 130 show a good accordance between the measurements and the CFD-calculation, where the maximum temperature of the finned zone of the cask is overestimated conservatively by maximal 4 K.

Due to the favourable ambient conditions compared to reality – i.e. lower temperatures for the outer surfaces of the neighbouring casks – additional safety margins occur, as the heat removal by thermal radiation of the chosen cask is overestimated, conservatively. Despite the more favourable ambient conditions, the temperatures at outer surfaces of the chosen cask are still overestimated.

The uncertainties of the thermography camera amounts to about 1 K, which is lower than the overestimation of 4 K at the outer surface for the cask at SP 130. This shows that the CFD-method for the fluid-mechanical and thermal design of the storage hall H in ZWILAG leads to conservative results. Additionally, more conservative boundary conditions are used in calculations for the thermal design of the storage hall H in ZWILAG, so that even higher safety margins are present. This validation can be used in the future, if operators of spent fuel assemblies and high active waste interim storage facilities need to store more casks than initially planned, or casks with higher decay heat loads. This demonstration would make it possible, from the thermal point of view, to use the existing storage hall rather than to build expensive structural extensions.

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