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COMBINATION OF ANALYTICAL AND NUMERICAL METHODS FOR THE FAST THERMAL EVALUATION OF TRANSPORT AND STORAGE CASKS

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ABSTRACT

Transport and storage casks (T/S-casks) for nuclear fuel elements have to fulfil a wide range of requirements, including the safe dissipation of decay heat, among others [1]. In order not to decrease the strength of the used materials, the maximum temperature within the cask has to be limited. Gas-filled gaps can have a big influence on the heat dissipation, as their conductivity is much lower than the conductivity of solid materials. At the same time, as convection and radiation exist as further heat transfer mechanisms next to conduction, fluids are more difficult to consider within Finite-Element-Analysis (FEA). Due to the small geometrical extents of gas-filled gaps in comparison to the overall cask dimensions and the three existing heat transfer mechanisms, FE-simulations considering such gaps can be very time consuming. Therefore, in cooperation with the Swiss Federal Nuclear Safety Inspectorate ENSI, a simulation tool was developed, which considers the thermal effects of gas-filled gaps for the fast thermal evaluation of T/S-casks.

Therefore, analytical equations are used for a gas-filled gap between inner and outer part of T/S-casks. This is done for both upright positioned casks during interim storage (annular gap geometry) and lying casks during transport (asymmetric gap geometry). In order to fasten the FE-simulation, a special boundary condition called Thermal Gap Condition (TGC) was developed, which is able to consider all heat transfer mechanisms in the gap without meshing it. This is done by using a specially developed Lagrange-Multiplier method, which is able to connect parts by using analytical equations. For an annular gap geometry of upright positioned casks it was already shown that fast simulations are possible, whereby radiation was neglected [2]. Now, main focus lies on asymmetric gaps with an alternating gap width by considering radiation at the same time. This means, a novel TGC is necessary, as different heat transfer equations have to be applied.

INTRODUCTION

T/S-casks for nuclear fuel elements have to fulfil several protection objectives, according to the guideline TS-R-1 [3], in order to ensure the safe transport and storage of the nuclear material. Basically, these protection objectives can be summarized as follows: containment of the radioactive contents, control of external radiation levels, prevention of criticality and prevention of damage caused by heat. In order to ensure compliance with these objectives, numerical methods are more and more important in the framework of the cask development next to experimental verification processes.

A particular challenge for numerical analyses regarding the thermal behaviour of T/S-casks poses gas-filled gaps. Due to a lower heat conductivity of gaseous fluids in comparison to metals, gas-filled gaps within T/S-casks can influence the temperature distribution within such casks significantly. Since not only heat conduction exists as heat transfer mechanism in fluids, but convection and heat radiation occur as well, the consideration of gas-filled gaps within numerical simulations leads to a higher computational effort as well as to an increased modelling expense, which is why such gaps are often neglected. Additionally, such gaps usually show very small geometrical dimensions in comparison to the overall cask dimensions, which makes them even more difficult to consider within thermal analyses. Here, the regarded gas-filled gap is positioned between basket and cavity wall and therefore divides the cask in an inner and an outer part. For upright positioned casks, usually a perfectly centred basket is assumed (see Figure 1, left), which is a safe assumption, as maximum temperatures are calculated [4]. For transport, the cask is in horizontal position, which is why the gap geometry transforms from an annular to an asymmetric gap (see Figure 1, right).

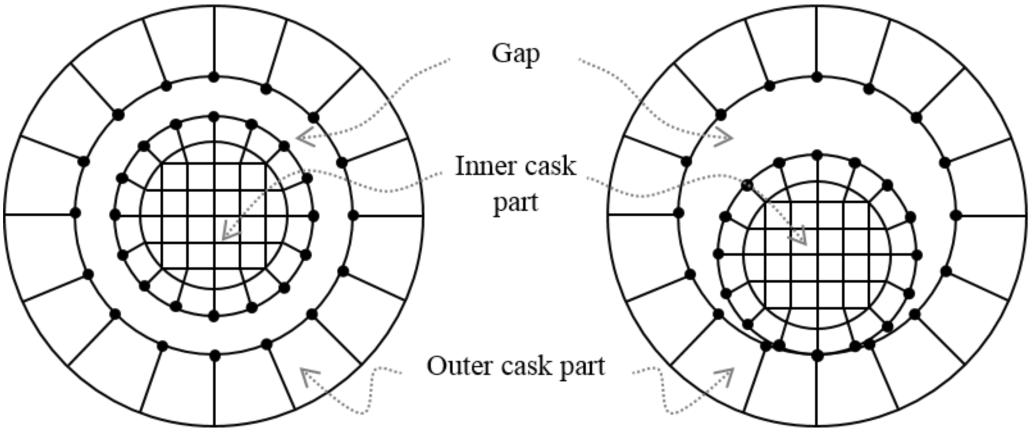

Figure 1. Schematic cask in interim storage configuration (annular gap, left) and transport configuration (asymmetric gap, right)

In a research project between the University of Bayreuth (Germany) and ENSI (Switzerland) an innovative simulation tool called Z88ENSI has been developed. This novel tool evaluates the thermal behavior of T/S-casks and their thermo-mechanical effects. Based on the Finite-Element system Z88 - developed at the Chair for Engineering Design and CAD of the University of Bayreuth [5] - analytical equations are integrated in this numerical software in order to accelerate the simulation. For an annular gap geometry of upright positioned casks it was already shown that fast simulations are possible, whereby radiation was neglected [2]. Now, main focus lies on asymmetric gaps with an alternating gap width by considering radiation at the same time.

THERMAL GAP CONDITIONS

As described in [2], the perturbed Lagrange-Multiplier method is used to include analytical equations in the numerical FE-system. In order to be suitable for installation as a thermal gap condition, an analytical equation must be found describing the heat flow through an annular gap or through an asymmetric gap based on a linear equation, so that the perturbed Lagrange-Multiplier method can be applied. For this purpose, an analytical equation must be created, which connects the temperature difference between the gap nodes of the inner cask part (index i) and the gap nodes of the outer cask part (index a) and sets it equal to the constant K.

$$T_i - T_a = K \tag{1}$$

The constant K on the right side of the equation can be calculated on the basis of any parameter, as long as there is no temperature dependence with respect to the gap node temperature. In case of horizontal positioned casks, this was done for each heat transfer mechanism (conduction, convection and radiation). In the following, only conduction and radiation are discussed, as they play the major role regarding the heat transport in the gap.

Conduction

Due to the asymmetric shape of the gap in the horizontal cask configuration, the local distance of the respective gap node pair must be taken into account. For this form there is no specific analytical solution for the calculation of the temperature difference. For this reason, the heat transfer between each node pair is considered as one-dimensional heat conduction through a flat wall (thickness s):

$$\dot{Q} = \frac{\lambda_{Fluid} A (T_i - T_a)}{s} \tag{2}$$

If this equation is resolved after the temperature difference so that it is suitable for installation as a thermal gap condition, an individual constant K_i results taking into account the local gap width s_i:

$$T_i - T_a = K_i \quad where \quad K_i = \frac{\dot{Q} s_i}{A \lambda_{Fluid}} \tag{3}$$

For the contact case, in which the solids of the inner and outer cask part touch each other, the local gap width s_i becomes zero. This causes, that the constant K is of the value of zero, too, which ensures ideal heat transfer between the pair of gap nodes as it corresponds to an ideal thermal solid-solid contact.

Radiation

The heat flux by heat radiation between two surfaces, to which the temperatures T_1 and T_2 are applied, is generally calculated by the difference of the fourth power of these temperatures, which are multiplied by the auxiliary value C_{12} and the view factor F_{12}.

$$\dot{Q} = F_{12} C_{12} A (T_i^4 - T_a^4) \tag{4}$$

In order to consider thermal radiation in asymmetric gaps in combination with thermal conduction, an equivalent thermal conduction coefficient can be calculated for thermal radiation. The equivalent thermal radiation coefficient λ_R is defined as [6]:

$$\lambda_R = 4C_{12}F_{12}sT_m^3 \quad (5)$$

This coefficient is added to the previous heat conduction coefficient of the fluid in the gap λ_{Fluid}, whereby a new conduction coefficient is calculated (index RC: radiation and conduction):

$$\lambda_{RC} = \lambda_R + \lambda_{Fluid} \quad (6)$$

So, if radiation has to be considered, this coefficient can be used for the gap condition presented in Equation 3 for lying T/S-casks. But as Equation 5 states, a mean temperature T_m must be known for the calculation of the heat transfer coefficient for radiation λ_R, which is not possible as the temperature in the gap is not known unless the system is solved. Therefore, an iterative approach has to be chosen. For this reason, the new simulation tool uses for a first iteration pure conduction as heat transfer mechanism and solves the temperature distribution in the cask. This way, the initial temperature values for the gap nodes are already known. Now, this results can be used to calculate the mean temperature T_m, based on pure conduction. For a second iteration, T_m owns an initial value and radiation is considered as well for the TGC. It could be shown, that two iterations are sufficiently accurate [7].
A further challenge is the required calculation of view factors. View factors are defined as the proportion of a radiation heat flow emitted from surface A_1 that hits surface A_2. For this reason, the view factor F_{12} between two random surfaces A_1 and A_2 with the Euclidean distance s can be calculated by [6]:

$$F_{12} = \frac{1}{\pi A_1} \int_{A_2} \int_{A_1} \frac{\cos\beta_1 \cos\beta_2}{s^2} dA_1 dA_2 \quad (7)$$

Despite the use of symmetry characteristics, the computing times are extremely high, which would multiply the runtime of Z88ENSI. For this reason, the numerical integration for the determination of the view factors is not implemented in the developed program Z88ENSI. In order to use the results of the view factors, they are pre-calculated and stored in Z88ENSI for selected nodes in the case of a horizontal casks. The view factors of the remaining nodes, which are not stored in the program, are determined by linear interpolation and assigned to the corresponding gap nodes. Since the calculation of the view factors is not carried out during the runtime of the program Z88ENSI, the calculation time for the determination of the radiation conductivity can be reduced significantly.

VERIFICATION OF THERMAL GAP CONDITIONS

For verification purposes a simplified cask model is used, as shown in Figure 2. No basket is modelled. As boundary conditions a heat source of 20 kW at the inner cask part and a temperature boundary condition (constant temperature of 80°C) at the outer cask wall is applied. Both cask parts are equipped with the same heat conductivity ($\lambda = 54\ W/mK$).

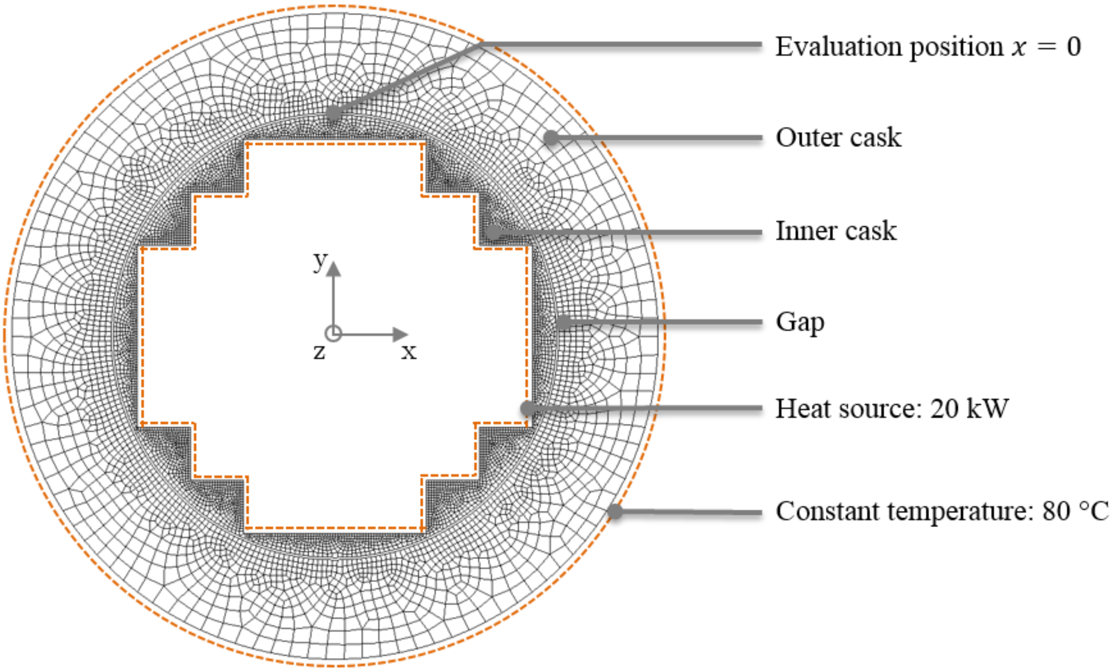

Figure 2. Simplified verification model including boundary conditions and evaluation position

The presented gap conditions for conduction and radiation have to be verified, which is shown in the following chapters. Therefore, Abaqus/CAE 2016 (by Dassault Systèmes) is used as a commercial FE-software.

Verification of Conduction

The thermal gap condition of a horizontal cask is verified on the basis of heat conduction as the only form of heat transfer. The gas-filled gap must be designed as a physical component in order to be processed with Abaqus in the FE-simulation. A constructed gap would be infinitely acute to the right and left of the linear contact area between the inner and outer cask part. For this reason, the contact area must be enlarged so that the gap geometry can be meshed. The inner and outer cask parts touch each other constantly in the form of a line contact. However, the gap, which becomes smaller, is cut off over a length of 100 mm in the positive and negative x-directions, so that no infinitely tapering shape can occur. Although this necessary adaptation results in differences between the models calculated in Z88ENSI and Abaqus, the adaptation is necessary to enable the meshing of the gap in a commercial FE-system. The thermal conductivity of helium is assigned to the new component asymmetric gap ($\lambda = 0.2116\ W/mK$). The results are summarized in Table 1.

It can be seen that the deviations are at most 2.63 % (deviation of the node temperature at position x = 0, where the largest gap width of 20 mm is present). The maximum temperature occurring in the cask is 177.0 °C in the case of Z88ENSI and 175.7 °C when simulated with the commercial software Abaqus. This corresponds to a relative deviation of 0.74 %.

Table 1. Comparison of the results between Z88ENSI (including TGC) and Abaqus regarding maximum temperature as well as selected gap node temperatures for heat conduction

	T_{max}	$T_{i,x=0}$	$T_{a,x=0}$
Z88ENSI	177.00 °C	174.45 °C	84.16 °C
Abaqus	175.70 °C	172.99 °C	82.01 °C
Relative deviation	0.74 %	0.84 %	2.63 %

Verification of Radiation

In commercial FE-systems, thermal radiation can be transferred between two surfaces separated by an unmeshed area. Superimposed, additional heat transfer mechanisms are not possible. For thermal radiation, a calculation model is used which automatically calculates the view factors. Since the presented verification model does not have a lid and bottom plate system, a small portion of the radiation energy escapes into the environment.

Identical boundary conditions are used. Furthermore, the emissivities ε_1 and ε_2 must be specified both in Z88ENSI and in Abaqus. Both values are assumed to be $\varepsilon_1 = \varepsilon_2 = 0.5$. These emissivities are chosen as examples and can be defined by the user in later Z88ENSI applications.

Since Z88ENSI's gap condition for thermal radiation is based on the gap condition for thermal conduction, a very small value for the thermal conductivity of the fluid (here: 0.00001 W/mK) is used to suppress the influence of thermal conduction. In order to exclude an influence of the iterative solution finding in Z88ENSI, the number of iterations for the calculation of the gap condition is increased to ten. This is necessary for this simulation because the thermal conductivity of the fluid is set to a very small value. Thus the temperature values calculated in the first iteration differ strongly from the results obtained in the further iterations, which is why the number of iterations must be increased in the sense of a good convergence behaviour.

Table 2 summarizes the verification results. The deviations detectable are a maximum of 2.35 % and can be evaluated as minor, whereby the verification of the thermal gap condition for radiation can be successfully completed.

Table 2. Comparison of the results between Z88ENSI (including TGC) and Abaqus regarding maximum temperature as well as selected gap node temperatures for radiation

	T_{max}	$T_{i,x=0}$	$T_{a,x=0}$
Z88ENSI	243.99 °C	239.59 °C	85.34 °C
Abaqus	242.30 °C	234.09 °C	86.53 °C
Relative deviation	0.70 %	2.35 %	-1.38 %

APPLICATION EXAMPLE

Using Z88ENSI it is possible to simulate arbitrary gap widths and load conditions automatically. Thereby, the user can choose, which heat transfer mechanisms shall be considered. For an exemplary

cask type, the influence of the heat transfer mechanisms in the gap (here: pure conduction and conduction plus radiation) is shown depending on the actual gap width. The cask model is based on the real cask type HISTAR 180 from Holtec International. All information used for the simulations presented here is based on publicly accessible sources [8]. Numerous information on details of the HISTAR 180 cask, such as geometric dimensions, material parameters or data on the actual load, are completely or partially confidential and for this reason made unrecognizable in the public safety report (see [8]). Therefore, assumptions are made for the exemplary modelling of the HISTAR 180 cask.
The basic dimensions of the HISTAR 180 cask, such as height or outside diameter, are publicly available [8]. On the basis of these sizes, it is possible to determine the approximate dimensions of the remaining cask components using assembly drawings and isometric cask views, so that the modelling of a simplified cask is possible.
As boundary conditions a heat source of 32 kW is used. At the outer cask walls a convective boundary condition is applied (8 W/m²K at 23 °C). Some of the material properties are not publicly accessible. Because of this, all temperature results are normalized, so only the qualitative differences between the examined simulations can be discussed. The results can be seen in Figure 3. The highest temperature results by use of radiation and conduction as heat transfer mechanisms at a nominal gap width of 10 mm (gap width of the equivalent annular gap) is therefore set to a normalized value of 100.

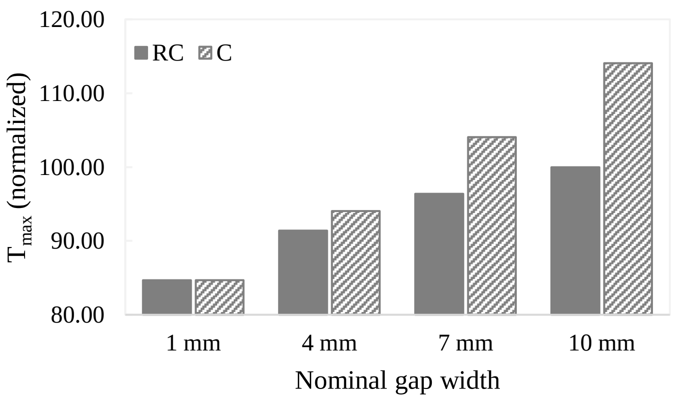

Figure 3. Influence of the type of heat transfer (RC: radiation and conduction; C: conduction only) in the gap as a function of the gap width for a cask in transport configuration

If thermal radiation is taken into account as a transmission mechanism in the asymmetric gap of the horizontal cask, the maximum temperatures drop significantly for larger gap widths, whereas no influence is discernible for smaller gap widths. Since a local gap width of maximum 20 mm occurs on the upper side (for the largest nominal gap width investigated, 10 mm), neglecting thermal radiation leads to a 12.35 % higher maximum temperature. The simulative integration of heat radiation in sufficiently large, gas-filled gaps leads to a significantly better knowledge of the actual temperature field in T/S-casks. With a nominal gap width of 1 mm, no influence of the heat transfer mechanisms on the maximum temperature is visible.

CONCLUSION

Thermal Finite-Element models of T/S-casks which consider all existing gas-filled gaps, would entail high modelling and computational efforts. Because of this, the University of Bayreuth in cooperation with ENSI developed a software tool that is able to provide an approximated thermal and thermo-mechanical evaluation of T/S-casks. Based on the completely independent Finite-Element system Z88, the software Z88ENSI significantly shortens the calculation duration. Using particularly developed thermal gap conditions, the thermal effects of gas-filled gaps can be considered by analytical equations without meshing the gaps. With this tool, fast and approximate evaluations of T/S-casks are possible. The maximum temperature in the cask due to different loading conditions and material parameters can be simulated. Both upright positioned and lying cask configurations can be simulated.

ACKNOWLEDGMENTS

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