THERMO-MECHANICAL INVESTIGATIONS OF THE SINQ "CANNELLONI" TARGET

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Abstract

Numerical results of three-dimensional ANSYS thermo-mechanical simulations of single components of the SINQ target system are presented. Thermal stresses are generated by energy deposition in so-called "cannelloni" consisting of a Zircaloy-2 rod filled with Lead to 90% of its inner volume. The molten region of the inner Lead filling is calculated by thermal analysis using the energy deposition profile imported from MCNPX calculations. Induced mechanical stresses are studied for a set of predefined parameters, the heat transfer coefficient and the bulk temperature of the heavy water cooling system. Critical stress regions are investigated to provide possible failure scenarios and overall system performance.

INTRODUCTION

The Swiss spallation neutron source SINQ at the Paul Scherrer Institut (PSI) Switzerland, is a continuous 1 MW research spallation neutron source [1]. SINQ is driven by a cascade of three accelerators, the final stage being a 590 MeV isochronous ring cyclotron which delivers a beam current of 2.2 mA. The current SINQ heavy water (D_20)-cooled rod bundle target is schematically depicted in Fig. 1. The target rod array is built from Zircaloy-2 tubes, which are filled with Lead. The volumetric fraction of the Lead inside the rods is about 90% to allow for the thermal expansion of the Lead during heating up and melting.

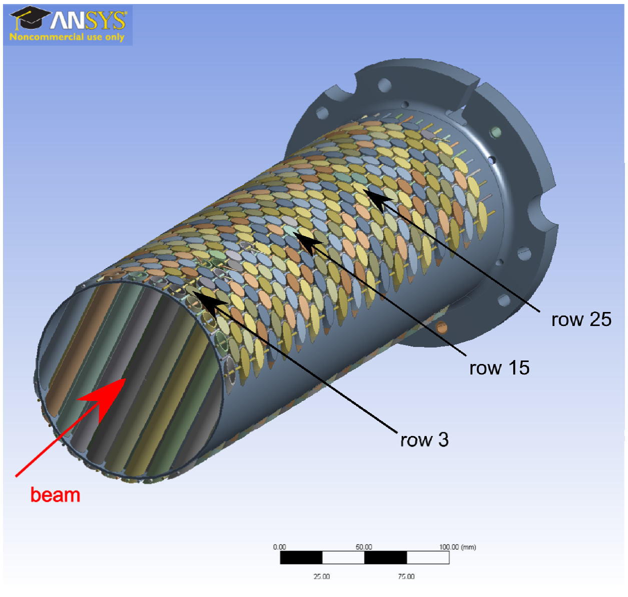

Figure 1: SINQ target rod bundle configuration.

The target configuration is vertical. The 575 MeV proton beam penetrates through an AlMg3 Beam Entry Window (BEW) and hits the rod bundle from below. Depending on the flow conditions, the power and pressure in the system, several flow and heat transfer regimes may occur inside the target assembly. In order to aid the design of current and future experiments, thermo-mechanical simulations have been performed at specific positions (row 3, 15 and 25 at the centre of the rod bundle) to study mechanical stresses induced by the thermal loads produced by the beam energy deposition.

WORKING PRINCIPLES

The ANSYS software version 14 [2] has been used to perform thermo-mechanical simulations of single components of the SINQ target system. Due to axial symmetry, only half of a single rod has been modelled. The rod is free to move in the axial direction, z axis in Fig. 2, but it is constrained in all other directions. The material properties of Zircaloy-2 and Lead have been selected based on extensive literature survey. Both Lead and Zircaloy-2 are ductile materials and the analyses are based on the failure theories for ductile materials.

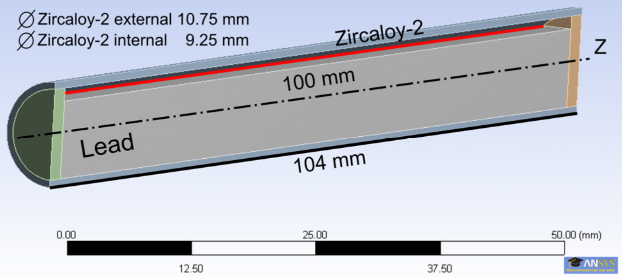

Figure 2: Geometry of a single "cannelloni" rod used for thermo-mechanical simulations.

The simulation matrix consists of 12 cases. Three beam energy deposition distributions fitted to MCNPX calculations have been considered, corresponding to different locations: row 3 where the energy deposition reaches its maximum, row 15 and row 25. Two different heat transfer coefficients have been selected (10'000 and 35'000 [W m^{-1} K^{-1}]), which encompass the expected operation values. Two failure theories were used to estimate the safety factors: the maximum equivalent stress and the maximum shear stress. The cooling fluid temperature is kept constant to the average value of 40 ºC.

The maximum equivalent stress failure theory estimates the safety factor as [2]:

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$$\mathrm{F_S} = \frac{S_y}{\sigma_e}$$

where S_y represents the material yield stress and σ_e is the maximum equivalent stress. The maximum shear stress failure theory computes the safety factor as [2]:

$$\mathrm{F_S} = \frac{f\,S_y}{\tau_{\max}}$$

where $f\,S_y$ represents a fraction of the material yield stress and τ_{max} is maximum shear stress. In this study, f is set to 0.5 corresponding to a conservative approach.

Figure 3 represents the fitting functions of the beam energy deposition distributions at different locations calculated using MCNPX [3]. The beam energy has its maximum in row 3 at the central location in the rod bundle, where the Lead is expected to be partially or completely molten.

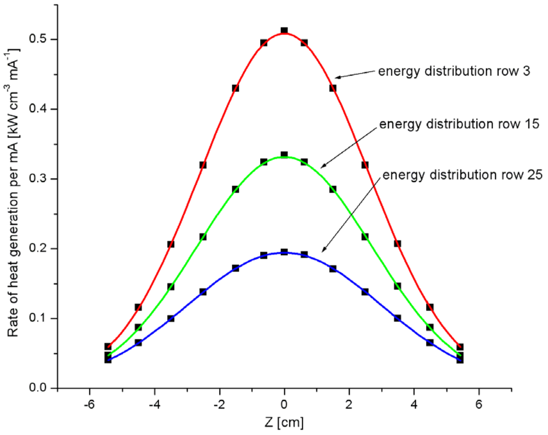

Figure 3: Beam energy deposition distributions at different locations fitted to MCNPX calculations.

Due to the long duty cycle of normal operation (400 s of pulse duration over 404 s of pulse period) steady-state simulations have been performed. To confirm this assumption, a transient thermal analysis for the energy deposition in row 3, see Fig. 3, with heat transfer coefficient of 10’000 [W m^{-1} K^{-1}] has been carried out. In Fig. 4 the time evolution of the average maximum and minimum temperatures in the Lead is shown. The beam is switched on after 4 seconds and kept on for 40 seconds. The maximum average temperature reaches the steady state plateau almost immediately after the beam is switched on and it remains constant until the beam is switched off at 40 seconds.

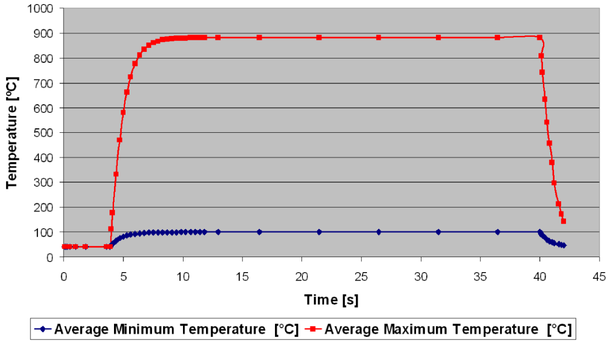

Figure 4: Time evolution of the average maximum and minimum temperatures in the Lead.

The simulation procedure was done in stages. Temperature distributions in the Lead and in the Zircaloy-2 have been calculated using ANSYS Workbench Mechanical with ANSYS Parametric Design Language (APDL) scripts to account for the spatial non-uniform volumetric energy depositions of the beam. The axial temperature profiles in the Lead from the centre of the rod were extracted to check if phase transition from solid to liquid has occurred. In row 3 and row 15, the Lead was molten for any heat transfer coefficient and the spatial extents of the fluid regions were recorded. In row 25 the maximum average temperature never reaches the melting point of the Lead (600.55 K). For the cases of phase transition, the ANSYS CFX fluid solver with CFX Expression Language (CEL) was used to model the fluid region. The mechanical analyses were performed with a 1-way coupling between ANSYS CFX and ANSYS Workbench Mechanical. In the cases where no phase transition occurred, the thermal and mechanical analyses were performed using ANSYS Workbench Mechanical with APDL scripts.

SELECTED RESULTS AND DISCUSSIONS

The aim of this work is to characterize critical stress regions in a single rod under different conditions and to determine possible failure scenarios. The safety factors are estimated with respect to tensile yields per material. The main concern is related to the integrity of the Zircaloy-2 external surface to avoid the spilling out of Lead with subsequent contamination of the cooling fluid and system performance deterioration. Figure 5 represents a combination of several results. From top to bottom, the safety factors using the maximum equivalent stress failure theory [4] for heat transfer coefficient of 10’000 [W m^{-1} K^{-1}] in row 3, 15, and 25 are presented. The critical stress regions are shown in red where the safety factors drop below 1.

In all cases the critical stress regions on the Zircaloy-2 external surface are located in the top parts and they originate where the void region starts (continuous red line in Fig. 2).

Figure 5: Safety factors using the maximum equivalent stress failure theory for heat transfer coefficient of 10’000 [W m^{-1} K^{-1}] and different beam energy profiles: (a) row 3, (b) row 15, and (c) row 25.

In the cases of row 3 and 15 a significant central part of the Lead is molten and the critical stress regions extend in the axial direction up to the interfaces between solid and liquid phases, Fig. (a) and Fig. (b). In the case of row 25 where no phase transition occurred, the critical region covers almost the full axial length of the rod, Fig. (c). Critical stress regions for heat transfer coefficient of 35’000 [W m^{-1} K^{-1}], show similar shapes with higher values of safety factors.

When the maximum shear stress failure theory [4] is used instead, the safety factors show higher values but similar shapes with respect to the cases computed with the maximum equivalent stress failure theory (figures not shown).

It must be pointed out that because the fatigue is not accounted for in this study, the localized yielding can lead to redistribution of stress and no real failure might occur [4].

SUMMARY AND CONCLUSIONS

A preliminary thermo-mechanical study of single components of the SINQ target system is presented. Specific operation conditions have been simulated to investigate possible failure scenarios in order to avoid the spilling out of Lead with subsequent contamination of the cooling fluid and system performance deterioration. Critical stress regions on the Zircaloy-2 external surface have been found, whose configurations depend on heat transfer coefficients and beam energy distributions and intensities.

In the regions where the beam energy deposition reaches its maximum, most of the Lead is molten. The motion of the fluid Lead can redistribute the thermal loads in the structure and, after re-solidification, the Lead can have different shapes than its original one. To have a more reliable picture of the system, the motion of the molten Lead should be taken into account. Additionally, a new set of simulations can be performed to investigate critical stress regions using the tensile ultimate strengths per material as failure indicator.

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