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Numerical flow simulation of the neutron source SINQ of PSI

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Abstract. The Swiss spallation source, SINQ, is in operation since 1996. Since its start-up a constant target development program has been pursued, which culminated in the operation of the liquid metal target MEGAPIE. However, the work-horse target consists of a bundle of Zircaloy-II rods filled with Lead, the so-called Cannelloni target. As the high intensity proton accelerator, HIPA, at the PSI constantly delivers higher beam currents to SINQ it is important to perform numerical simulations to understand the response of the target to the power deposition and to ensure the proper D₂O cooling of the Cannelloni rod bundle. Steady-state 3D fluid simulations of the heavy water coolant flow are coupled with the heat source terms in the Cannellonis. The source terms are described as UDFs (User Defined Function) for all Cannellonis with its Zircaloy-II tube and Lead filling. The energy deposition functions for the heat source terms are calculated using MPCNX 2.7.0. Major results from the CFD simulations are the flow structure with the resulting pressure field and the temperature distribution in the target. The results show good agreement with respect to the measured values during operation of SINQ. Additionally the local convective heat transfer coefficients (HTC) are calculated.

1. Introduction

The simulations presented here investigate the D₂O cooling of the Cannelloni target of the Swiss spallation neutron source SINQ. The target consists of a bundle of Zircaloy-II tubes filled with the Lead, the so-called Cannelloni target. The volumetric fraction of the Lead inside the tubes is 90% to allow for the thermal expansion of the Lead during heating up and melting. It is of paramount importance to correctly characterize the flow behaviour in order to predict the heat dissipation from the Cannelloni to the coolant fluid, D₂O. In the present study, the turbulent flow is approximated using the RANS (Reynold-Averaged-Navier-Stokes) formulation with the Shear Stress Transport (SST) turbulence modelling, together with temperature dependent material property values. In the simulations temperature dependent material properties for Zircaloy-II [1][2], Lead [1][3][4][5][6] and heavy water [7] were used. A mass flow rate of 10 kg/s (full target) at 40°C is assumed as starting condition.

2. Basics

A common method for the calculation of turbulent flows is the Reynolds-Averaged-Navier-Stokes (RANS) modelling. In this method, the Navier-Stokes equations are solved for time-averaged flow behaviour and the magnitude of turbulent fluctuations. A hexagonal mesh was set up using ANSYS ICEM for the fluid and the solid part of the simulation. Great care was taken to resolve the near wall...
region, i.e. the fluid region close to the solid of the Zircaloy-II tube. For the simulation a Coupled-Solver-Algorithm is used with Second Order Formulation. This pressure-based coupled algorithm obtains a robust and efficient solution for single phase steady-state flows [8].

2.1 Turbulence Model

The Shear Stress Transport (SST) Model is used in this study [9]. It is a robust and accurate formulation of the k-ω-Model in the near-wall region with the freestream independence of the k-ε-Model in the far field.

2.2 Heat Transfer Equations

In the simulations the heat flux is computed from two sides. One description used the heat flux to a wall from a fluid cell.

\[ q = h_f(T_W - T_f) + q_{rad} \]

Here \( q \) is the local heat flux, \( q_{rad} \) is the local radiative heat flux and \( h_f \) is the fluid-side local convective heat transfer coefficient. \( h_f \) is calculated using the local flow-field conditions (e.g. turbulence, temperature, velocity, etc.). The temperature difference is calculated using the wall surface temperature \( T_W \) and the local fluid temperature \( T_f \) [8].

From the solid cell the heat flux is calculated using the thermal conductivity of the solid \( k_S \), the local solid temperature \( T_S \) and the distance between wall surface and the solid cell center \( \Delta n \) [8].

\[ q = \frac{k_S}{\Delta n} (T_W - T_S) + q_{rad} \]

With these two equations the boundary conditions at the wall can be calculated. In the simulations for the SINQ target the radiative heat flux \( q_{rad} \) was assumed to be zero.

3. Geometry

![3D geometry of the SINQ Cannelloni Target.](image)
In order to reduce the computational time and due to the inherent symmetry of the SINQ target structure, only a quarter of the 3D geometry is used (Figure 1). In order to prevent numerical reverse flow at the outlet the length of the upper part of the geometry has been extended to a length, $L$, of about 10 times the hydraulic diameter, $D$: $L_{turbulent} \approx 10 \times D$ [10].

The Cannelloni's outer diameter is 10.75 mm, their inner diameter 9.25 mm. The Target holder hydraulic diameter is $D = 122$ mm. The incoming cold flow (40°C) is split into two parts: the by-pass and the main flow around the Cannelloni. In the model the Cannelloni are built by three parts: Solid 1, Solid 2 and “Deckel” (lid) 1). Solid 1 represents the 90% Lead filling, the Solid 2 the Zircaloy-II tube and the “Deckel” 1 the end cap of the Cannelloni made from Zircaloy-II (see Figure 1). At the bottom of the target (the target is mounted vertically in SINQ) the incoming flow is split in two parts – the main flow, cooling the rod bundle, and the by-pass cooling the blanket structure of the target.

4. Heat Source (UDF – User Defined Function)

The incident proton beam and secondary particles produced deposit energy in all parts of the target, the Cannelloni, the blanket and of course also the coolant –D$_2$O. For the moment the heat deposition in the coolant is discarded as it is low compared to the energy deposited in the solid parts of the target. The incoming proton beam is approximated by a double Gaussian distribution. As a consequence also the heat source can be defined by a double Gaussian distribution, described by $f_1(y)$ and $f_2(x)$ in y- and x-directions.

Units are rescaled from MCNPX (kW/cm$^3$/mA) to Fluent (W/m$^3$) and a proton current of 1.5 mA is used. $f_1$ and $f_2$ read:

$$f_1(y) = \frac{A_{1,1}}{s_{1,1}} \cdot \frac{e^{-\frac{2y^2}{s_{1,1}^2}}}{\pi^\frac{1}{2}}$$

and

$$f_2(x) = \frac{A_{2,1}}{s_{2,1}} \cdot \frac{e^{-\frac{2x^2}{s_{2,1}^2}}}{\pi^\frac{1}{2}}$$

where $A_{1,1}, A_{2,1}, s_{1,1}$ and $s_{2,1}$ are values from the MCNPX calculations for Lead and Zircaloy-II [11]. To take into account the variation of the power deposition along z-direction, energy is calculated for each Cannelloni separately. The energy deposition of Zircaloy-II and Lead is described by the functions $f_1(y)$ and $f_2(x)$ and a scaling factor $c$ for convert the units to Fluent.

$$f(y, x) = c \cdot f_1(y) \cdot f_2(x)$$

5. Results

The simulation (Figure 2) shows the z-component (the main component of the velocity field), where z-direction points upwards. For the following discussion only the magnitude of z-component will be considered. The positive and negative sign give the direction due to the position of the reference system. The velocity increases at the top of the main inlet (a), where the channel was narrowed from the top very wide section to around 5 m/s. The z-velocity component has a maximum value of about 15 m/s in the inlet region of the bypass (b). The simulation shows also a large mass flow stream along the area between the outer Cannelloni and the holder wall (c). This causes an asymmetric flow in the target with high fluid velocities in the rim areas of the target. The inlet channel widens at the bottom end (d) inducing a decrease of the velocity. Due to the large expansion in point (e) the velocity reaches a relative minimum value.
A detailed view with velocity magnitude vectors (Figure 2, right) shows the flow behaviour in an elementary cell composed of 3 Cannelloni located at the center of row 6. A flow separation zone in the upper region of the Zircaloy-II tube with respect to the flow direction is visible. The flow separation angle is found to be 22°, see Figure 2, everywhere in the target. This dead water volume results in a bad cooling of the Zircaloy-II rod. In addition to the flow separation at 22° flow fluctuations at larger angles are found. However, these are not present everywhere and are believed to appear/disappear in time.

Figure 3 (detailed view) shows the temperature distributions in the Cannelloni and the heavy-water, as well as the static pressure in the system. The simulation uses the temperature-dependent heavy water properties from [11]. The temperature distribution (Figure 3, left) reach a maximum temperature of 536°C in the central Cannelloni of row 2 (Figure 1, Row 2 Cannelloni 5). The simulation (Figure 3, middle) predicts a heavy water temperature increase from 40°C (inlet conditions) to around 60°C in the outlet region. During operation D₂O temperatures of 70°C are measured in this region. The calculated temperature distribution indicates that from row 14 upwards the Lead is below its melting point of 327°C.

Figure 3, right shows the distribution of the static pressure. The simulation with the inlet-profile and the temperature-dependent heavy water properties give a pressure drop very similar to the measured one of around 1.25 bar.
Figure 3 Temperature distributions in the Cannelloni, the heavy water and the static pressure

Figure 4 Evaluated Heat Transfer-Coefficients of the SINQ Target
The fluid-side local convective heat transfer coefficient (HTC) is computed based on the local flow-field conditions, which vary from point-to-point. Thus there is no a constant heat transfer coefficient. The right picture in Figure 4 shows the distribution of the local convective heat transfer coefficient at the Cannelloni surfaces for the central Cannellonis of row 2 and 4. A decrease of the local heat transfer coefficient along the flow direction from 35000 $W/m^2K$ (central Cannelloni in row 2), to 25000 $W/m^2K$ (central Cannelloni in row 14) and 18000 $W/m^2K$ (central Cannelloni in row 24) is observed. The highest local heat transfer coefficients are always found at the bottom side of the Cannelloni with respect to the flow (z-)direction. This behavior is due to the dead water zone and void region above the Lead (90% filling) in each Cannelloni.

The evaluated local heat transfer coefficients serve as an input to FEM-simulations to evaluate the Cannellonis response to the thermal stresses induced by the proton beam.

6. Conclusion

Simulation have performed to characterise the flow and cooling behaviour of the SINQ target. A hexagonal ICEM mesh has been used together with the SST model in Fluent. Predicted $D_2O$ temperatures and the pressure drop agree quite well with measured values during operation. The evaluated local heat transfer coefficients serve as an input to FEM simulations for stress analyses. Besides the ICEM mesh other, semi-automatically produced meshes have been used in the simulations, but are not presented in this paper. These mesh study showed that fine enough, semi-automatically produced tetrahedral meshes are as well suitable to solve the current model giving similar results.

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