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Recent Computations and Experiments for Water-Cooled Rod Bundle Targets Development at PSI

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Abstract

The main objective of the activities in the fields of thermal-hydraulics and structural mechanics performed by Target Development Group (TDG) at the Paul Scherrer Institut (PSI), which comprise extensive computational and experimental studies, is to investigate various designs and cooling capabilities of the components and parts of spallation targets and to analyse hydraulic, structural and thermal behaviour of the target systems. The design and optimization of spallation targets with high heat deposition densities is a continuous effort using the latest version of Monte-Carlo particle transport (MC), commercial Computational Fluid Dynamics (CFD) and Finite Element Methods (FEM) codes. Various examples shown in this paper illustrate modelling and experimental procedures employed in the target development at PSI.

Introduction

One of the principal objectives of the TDG activities is to deal with overall coolability of the currently operated water-cooled rod bundle target, local coolability of the single rods at locations where high power is deposited and full structural integrity. The following sections summarize some of the most interesting findings and show some operational data.

1. Conceptual Design of a Water-cooled Rod Bundle Target

The current SINQ heavy water (D_2O)-cooled rod bundle target is schematically depicted in Fig. 1. The target rods array is built from Zircaloy-2 tubes, which are filled with lead. The volumetric fraction of the lead inside the rods is about 90% as it is necessary to allow expansion of the lead during heating up, melting and establishing of possible buoyant flow. The target configuration is vertical, that means the 575 MeV proton beam hits the target from below. The proton beam penetrates through the AlMg3 proton window (cusp shaped) onto the rod bundle. The inverted conically shaped cusp reverses the water flow (10 kg/s, 7 bar) coming down through the annulus and to direct it through the main guide tube where the rod bundle is situated. The BEW is cooled with an additional water flow (2.5 kg/s) passing through the narrow channel between the two containment hulls. The heat deposition profile for the target, under normal operating conditions, has been calculated for the target lead and the structural components (rods) by using MC calculations with MCNPX 2.5.0 (see for example in [1]). The maximum power deposited into the target material (lead) located in a single rod reaches 480 W/cm^3 at a total beam current of 1.5 mA. Total power deposited in the domain at the bottom of the target (radius = 5.5 cm, height = 11 cm) (where the power density reaches its peak) is about 257 kW for the proton beam current of 1.5 mA. Depending on the flow conditions, the beam current and the pressure in the system, several flow and heat transfer regimes may occur inside the target assembly. It is very well known that at moderate heat fluxes, typically around 20% of the critical heat flux, nucleation may occur in the wakes of the horizontal tubes. These regions may be the areas of incipient boiling. The nucleate boiling is usually followed by the regime of net vapour generation. This flow regime connected with incipient boiling is often called bubbly flow regime. As the space between the rods is confined, bubbles may merge and form big slugs. Due to large buoyancy forces these slugs accelerate upwards, whereas the bubbles in a tail may move downwards. Therefore, the coolant flow can be characterized as a complex two-phase flow in some scenarios.

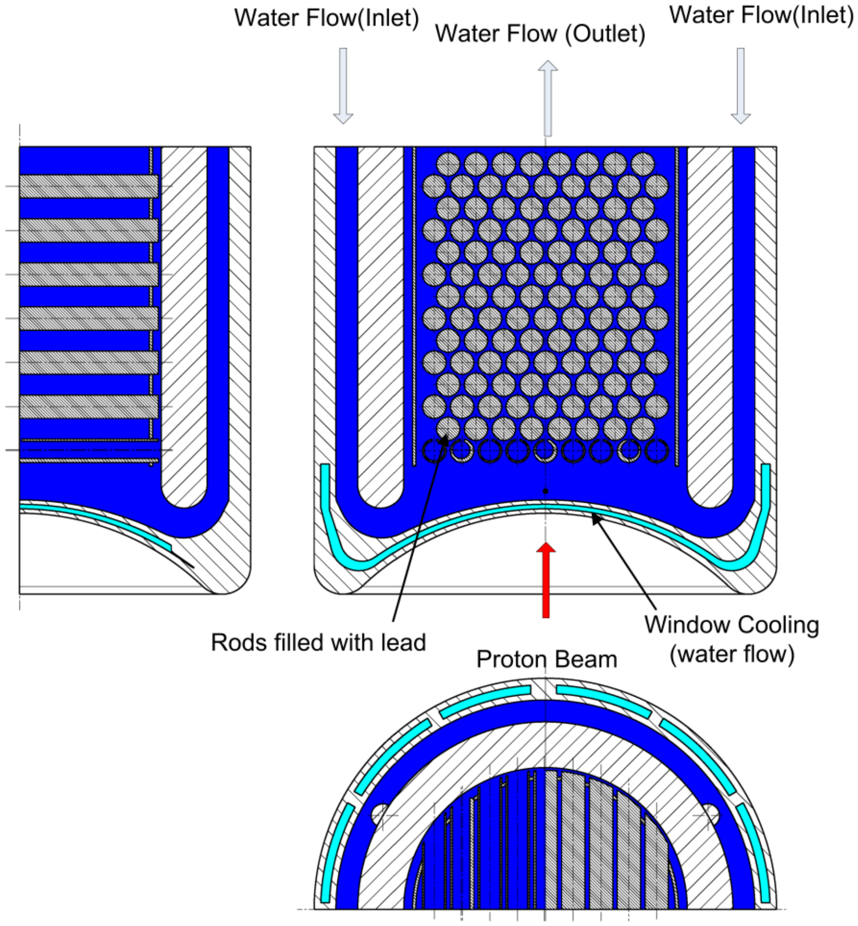


Fig. 1. Water-cooled rod bundle target operated at PSI

2. CFD and FEM for Target Development

The development of the water-cooled rod bundle target was also affirmed by CFD [1]. Reliable and accurate predictions of flow patterns and temperature distributions are key issues which contribute to safety. Two main building blocks, which demand careful consideration during application of general-purpose CFD code for complex geometrical configurations, are the turbulent shear stress and turbulent heat transfer modeling. Since there is no accurate prediction of the temperature field and structural thermal stresses without accurate prediction of the velocity field, the choice of turbulent shear stress models incorporated in commercial CFD codes demands careful selection, as well as mesh adaptation and iterative calculations. For instance, the knowledge accumulated over the last years demonstrated that the isotropic k–ε model is insufficient for accurate prediction of flows in a rod bundle. Therefore, any inappropriate parameter settings may simply lead to incorrect prediction of the temperature field, and as a consequence to wrong predictions of thermal stresses and structural behavior.

The following example shows the comparison between operational and computational data of the current SINQ target. The computational data were obtained for various boundary conditions.

3. Heavy Water-Cooled Rod Bundle Target (RBT): Rod Temperature Monitoring

The operating RBT contains a view solid Zr-2 cylinder, equipped with thermocouples, see Fig.2. In the simulation a volumetric heat is deposited inside the solid Zr-2 domain according to a calculated heat deposition profile (not given here). The tube is fixed at both ends in all directions (no translations and/or rotations), which can be considered as a worst case scenario. A uniform distribution of the convective heat transfer coefficient is assumed.

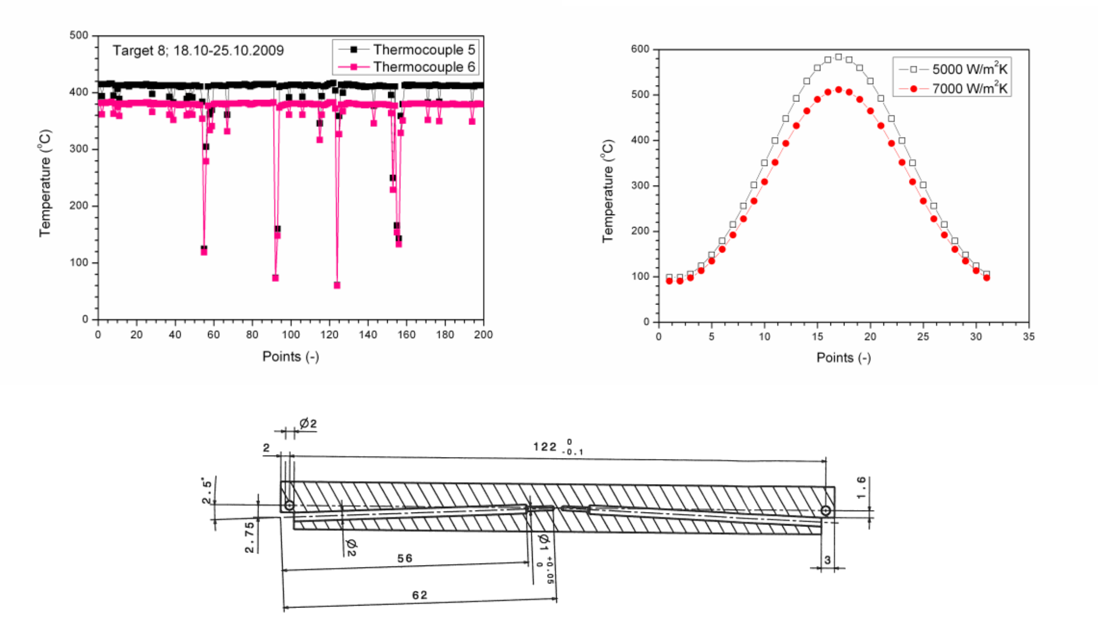


Fig. 2. Measured operation temperatures inside the Zr-2 rod (upper left); in the upper right picture calculated temperature profiles for constant heat transfer coefficient, at the centerline of the Zr - 2 rod, are given. The shift between nodes along the centerline is about 3.7 mm. The thermocouple setup is shown in the bottom picture

Operational results are presented in Fig. 2 upper left. The averaged temperatures are at about 420°C and 380°C for thermocouples 5 and 6, respectively (rough estimate, temperature drops are excluded). The calculated peak temperature at the rods' centerline drops when increasing the heat transfer coefficient (see Fig. 2 upper right) for the same heat deposition source term. From this information, the average heat transfer coefficient can be iteratively be determined by using experimental data. The calculations were done with the ANSYS code. It can therefore be stated, the knowledge about spatial distribution of the heat transfer coefficient for the corresponding inlet condition at the rod bundle entrance is crucial for temperature and thermal stress predictions.

4. Experiments for Target Development

The following parameters are experimentally determined during extensive testing of target structural components and configurations: integral hydraulic parameters (flow rate, pressure drop), local velocity distribution and turbulent properties, local pressure and pressure fluctuations, temperature and temperature fluctuations, overall and local heat transfer data, structural mechanical parameters (structural acceleration and velocity, strain and stress), parameters for cavitation detection and system health monitoring (structural acceleration, sound pressure, acoustic emission). In the following sections some of the most interesting experimental results conducted over last years by the TDG group are presented to demonstrate the developed procedure for components testing and to show important findings.

4.1. Rod Bundle Heat Transfer Measurements

During regular operation of a SINQ target a proton beam current of 1.5 mA (575 MeV) hits the target. Since an upgrade program of the PSI accelerator, which aims to improved operational reliability and to increased beam intensities, has been successfully conducted in 2009-10, an increased proton beam current of 2 mA can be supplied to the SINQ target in the near future. As the maximum heat deposited in the target material would then reach 640 W/cm^3, the thermal-hydraulic and structural behavior of some target rods can be significantly affected. One way to verify the cooling principle of a single rod filled with lead at high power deposition is a successive experimental investigation coupled with computational studies. Namely, it is of crucial importance to determine the convective heat transfer coefficient at various locations along a rod in a bundle for realistic initial conditions as they exist in the current target as well as to investigate the thermal-hydraulic and structural behavior of the single rod during transients, which include the phase-change of lead for various cooling conditions. An experimental set-up (Fig. 3) has been designed to accomplish the desirable experimental investigations. The inlet conditions can be varied by shifting the jet nozzle (Fig. 3 right). The inlet velocity profile and the turbulent properties are measured by a Hot Wire Anemometer (HWA). The local distribution of the heat transfer coefficient is measured by Hot Film Anemometer (HFA). The experimental results can be directly be mapped into the computational studies. Such coupling approaches provide reliable theoretical results, which are to be compared with the operational data and used for the estimation of maximal thermal stresses.

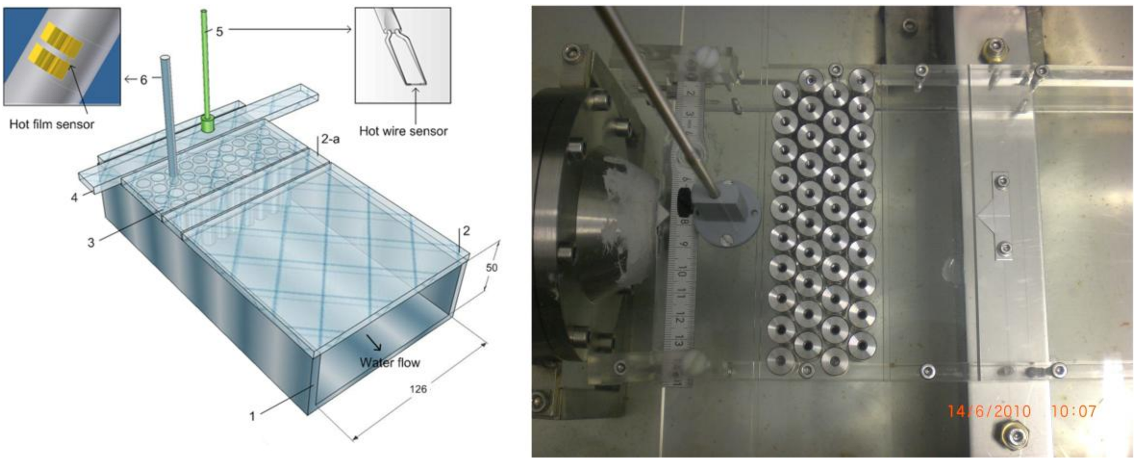
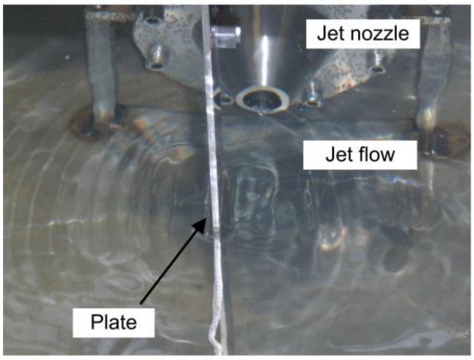


Fig. 3. Experimental set-up for heat transfer measurements at the outer surface of a rod in a bundle with HFA (scene on left): 1- test channel, 2 and 2a - plexiglas cover, 3 - rod bundle, 4 - manipulator for HTA, 5 - HWA, 6 - HFA

4.2. Detection of Structural Impact

The possible sources of transient short-term signals in the experimental or any other operational system may be the structural resonances due to the flow induced vibrations, the collapsing of the cavitating flow near solid structure (i.e. blades or at inner surfaces of the guide tube), non-balanced loop vibrations, problems during pump operation, system failure etc. In order to search for above mentioned transient (non-stationary) behavior hidden in the stationary time-dependent series, advanced data analysis must be performed. For this purpose, various data samples with various, but specified number of samples (2^n, n=10,11,12,13,…) have been analyzed by using digital filtering technique. As transient signals are of short time duration and totally varying in nature (amplitude, frequency and phase), the digital filtering and/or advanced time-frequency analysis method (Short-Time Fourier Transform, Wavelet analysis) may play a crucial role for the detection of abnormal system behavior. For example, if the structural resonance due to any known or unknown reasons exists in a system, it will be possible to examine its nature, as the corresponding signal can be extracted and de-noised. Classical methods, which involve FFT (Fast Fourier Transform) and the estimation of the power spectrum (the square of the magnitude of the FFT) are used as well. The power spectrum of a signal shows the relative intensity of the energy of a signal at each frequency for the entire signal. Therefore, the power spectrum characterizes how the energy of a signal is distributed in the frequency domain. In addition, as the Fourier transform, provides information about the frequency domain, the time-localized information is essentially lost in the process. Optionally, in order to reduce the noise in the signal, digital filtering with low pass, band pass or high pass filters were performed on data sets. Filtered data can be further analyzed with above described methods.

In order to find and localize various structural impacts on a plate in low and high Reynolds flow, the high-frequency sub band filtering of the signal is performed. The experimental installation is show in Fig. 4 left. Since the structural impact, which was externally and occasionally imposed on the plate, modifies the high-frequency sub-band oscillations, it could be successfully filtered out. The signal and the extracted structural impact are shown in Fig. 4 right. It is clearly indicated when it occurred. For this purpose the 4th order Butterworth high pass filter was used. The cutoff frequency was 300 Hz.



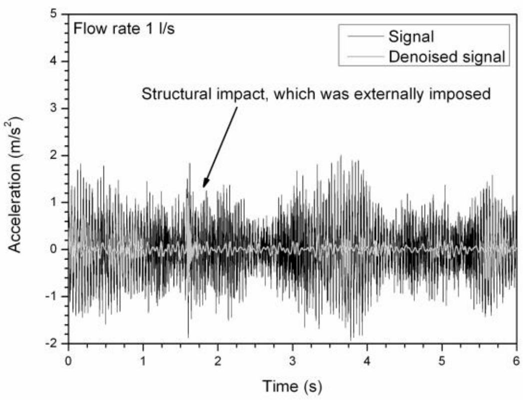


Fig. 4. The experimental installation for testing system health monitoring instrumentation and methods (left); detection of a structural impact, which was externally imposed on the plate (right)

Based on processing and analysis of the data bases acquired from above listed experiments, a real time data acquisition and signal processing has been developed for monitoring target behavior during operation. For that purpose two acceleration sensors have been installed on the operating SINQ targets' head (most upper part of the target) as shown in Fig. 5 left. First results (Fig. 5 right) show that sensor (No. 1) responds to a proton beam stimulus.

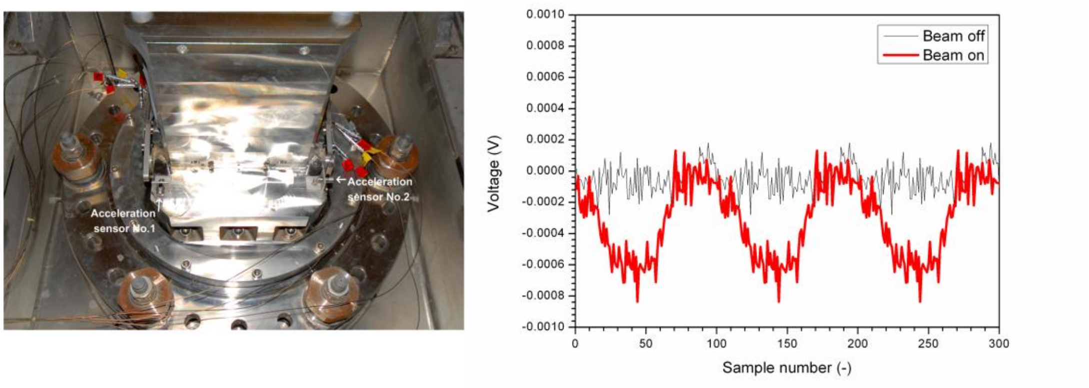


Fig. 5. Acceleration sensors installed on the operating SINQ target head (left). Signals for cases with and without proton beam stimulus (right). Sampling frequency was 20 kHz

Conclusions

In the last years extensive computational and experimental work related with development of the high power spallation targets have been conducted at TDG at PSI in the field of thermal-hydraulics and structural mechanics. The research activities regarding rod bundle targets are driven by various in-house projects. Several small and large scales experimental facilities equipped with modern data acquisition systems, measurement techniques and instrumentation have been developed, constructed and built.

Most interesting results and experimental set-ups, which are presented in this paper, reflect and highlight the importance of continuous target development activates conducted by the TDG; special focus was put on reliability and safety issues related with the design and operation of facilities with high power targets.

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