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Internal geometry and coolant choices for solid high power neutron spallation targets

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ABSTRACT

The next generation of neutron spallation sources envisages high power proton beam interaction with a heavy metal target. Solid targets have potentially higher spallation efficiency due to the possibility to use metals with higher density than used in liquid metal targets, but to realize this potential the solid fraction must be high enough. As the power released in the form of heat can reach several MW in the target volume of typically 10 l, target cooling can be a serious challenge. Heat evacuation efficiency for different solid fraction geometries at high power is analyzed for different coolant options (helium, water and gallium) using empirical correlations for friction factors and Nusselt numbers. For estimation of the heat transfer efficiency a parameter γ is introduced characterizing how many watts can be transferred per temperature- and pressure-difference unit. It is demonstrated that water is preferable as a coolant in high convection cases whereas gallium – in medium Peclet number cases when heat conduction in the coolant is important. Strictly focusing on cooling, the results indicate that for a stationary target liquid metals are advantageous in particular conditions. Three options are compared featuring geometries with large internal surfaces and avoiding high pressures. The transition from a stationary target to a rotating one in the case of gallium as coolant improves the heat transfer conditions to a higher degree than for ordinary liquids or gases. An advantage of gallium can be derived from the fact that gallium also acts as a neutron generating medium allowing the target solid fraction to be reduced and a part of the deposited heat is localized in coolant directly.

1. Introduction

The proper choice of materials for a spallation target is a multi-dimensional task and demands proper weighting and trading-off of a number of diverse requirements and boundary conditions [1]. Amongst other, factors like licensing issues, expected safe and reliable operation for decades, cost-efficiency over the whole life cycle of a facility up to decommissioning and disposal have to be taken into account.

Even focusing on cooling, detailed analysis of the different options for the optimal target construction requires considerable numerical simulation work and prototype testing. The solid structure has an impact on target thermo-hydraulic features, i.e. total surface area and – together with coolant properties – pressure difference and required temperature difference for transferring a given power. In particular, the choice of coolant can have a considerable impact on the whole target setup.

In several proposed designs the proton beam interacts with a solid tungsten target which is cooled by helium or water [2]. None of these coolants acts as a spallation medium, therefore the target brightness is largely determined by the solid tungsten volume fraction, the smaller the fraction the lower the neutron generation efficiency from the unit volume of the target. Coupling efficiency between target and (cold) moderators might benefit from a compact neutron source. Thus, for assessing the overall efficiency of producing suitable neutrons in the end one needs to take into account rather detailed geometric boundary conditions and requirements going beyond heat removal.

An alternative option to water is to use liquid metals [3,4], having two advantages: the coolant itself acts as a neutron generating medium, therefore the solid metal volume fraction can be reduced allowing more space for cooling channels, and at the same time pressure difference across the target can be reduced. While some liquid metals have been used in nuclear industry for quite a long time [5], gallium is a relatively new material in these applications with a potential for use as a coolant in next generation nuclear reactor systems [6].

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A qualitative comparison of different concepts can be made without very detailed data and the advantages and drawbacks of different coolant options can analyzed on the basis of simple models, describing the key properties of the target thermal hydraulics. This approach is used in the present paper for comparing different coolant options (water, helium and gallium) in simple models, i.e. a solid target comprising a block with cooling channels, rods, blocks or spheres in various packings. The three coolant choices represent high, medium and low Prandtl number liquids or gases.

2. Target model

For this study, a target volume $V = wdh$ with dimensions $w = 0.2x$, $d = 0.6$, and $h = 0.06$ m in x, y and z directions is considered. This corresponds to the planned ESS proton beam caused heat deposition volume with total heat power of 3 MW [1]; this value is used in analysis. The solid fraction φ is chosen to be 0.645 as in the existing solid SINQ target [7] which has been operated at MW power level.

The solid part of the target inside this volume is baselined to be formed of most widely used simple geometrical structures: solid block with channels, rods, and solid blocks with slits or simple cubic (SC), body centered cubic (BCC) or face centered cubic (FCC) sphere packings (Fig. 1). Here, the building blocks are taken to be of equal size all over the total volume. In a real and optimized target one can vary the characteristic dimensions according to local requirements given by the heat deposition or other boundary conditions.

For each geometry a governing coolant flow direction can be oriented in the beam direction (y axis direction) or perpendicular to it. For some geometries there is only one possible flow direction (for channels), others allow 2 (for slits) or 3 (for rods or spheres) different directions. The y direction orientation represents the highest flow path length (and hence associated pressure difference), the z direction – the shortest, thus the real channel configuration will be between these two limits. Therefore we will consider only the flow (and channels and slits) orientation in x direction as the most representative of a real target. Rods can be flush aligned (as in Fig. 1) or (like in SINQ [1]) staggered and tighter packed; here, we aim for the highest densities and staggered arrangements. Furthermore, it does make a significant difference whether rods are cooled by flow along their axis or in cross flow, making them more similar to slit- or sphere-based geometries, respectively.

An increase of the solid volume fraction quite generally reduces cooling efficiency and leads to an increased temperature difference between the coolant and the target material and to a higher pressure difference across the target as well as increased turbulence. At a fixed solid fraction value the real solid geometry determines the total interface surface area between the coolant and the target material. The larger the contact area, the smaller temperature difference is necessary to transfer the power deposited in the solid.

3. Internal surface area

At fixed solid volume fraction φ for a volume V the sole parameter which determines the internal surface area S is the diameter D of channels, rods or spheres. For slits D is the slit width. For channels, rods or slits the corresponding formulas are (note the somewhat "inverse" meaning of D for channels compared to rods)

$$S_c = \frac{4V(1-\varphi)}{D}, \quad S_r = \frac{4V\varphi}{D}, \quad S_s = \frac{2V(1-\varphi)}{D}, \tag{1}$$

for SC, BCC and FCC sphere packings

$$S_{SC}(0.52) = \pi\frac{V}{D}, \quad S_{BCC}(0.68) = \pi\frac{3\sqrt{3}}{4}\frac{V}{D}, \quad S_{FCC}(0.74) = \pi\sqrt{2}\frac{V}{D}. \tag{2}$$

The dependence of the parameter SD/V on the solid fraction φ is shown in Fig. 2. At fixed value of D it describes the area per unit volume; thus it can be useful to compare different geometries. For slits and channels this parameter decreases with the increase of the solid fraction. For rods geometry the surface area increases

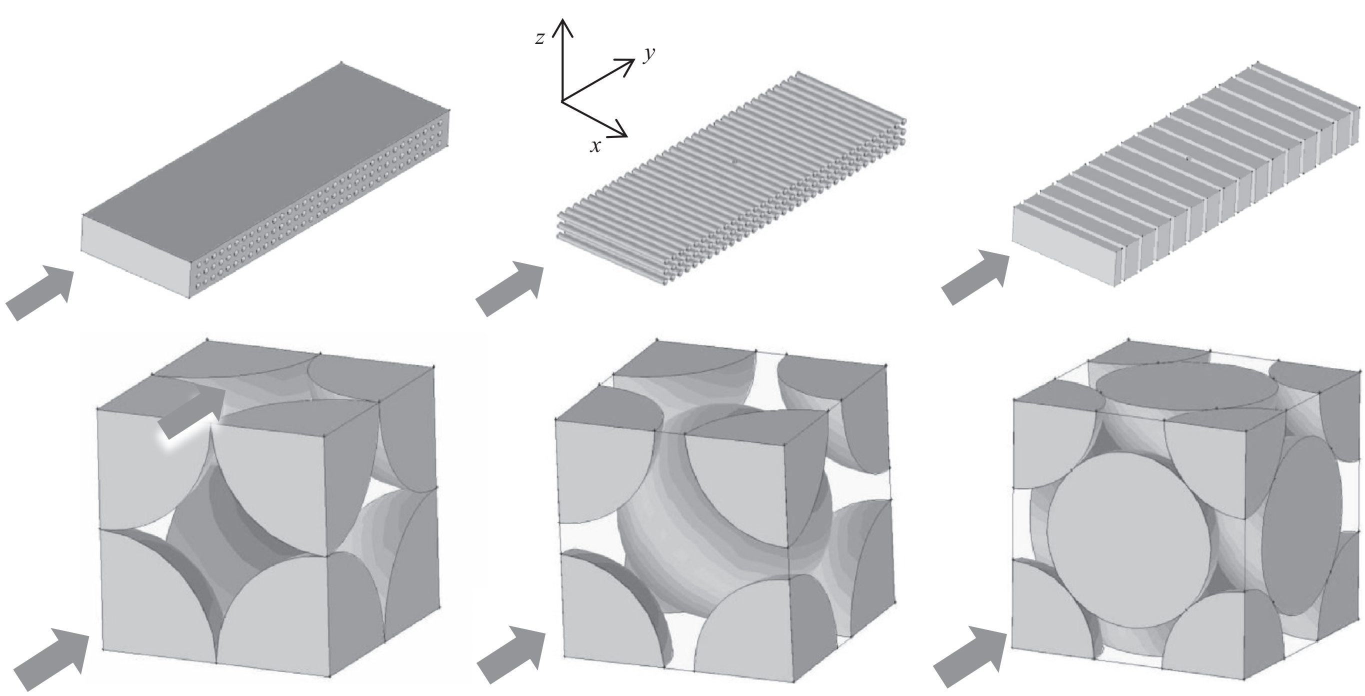

Fig. 1. Target models with cooling channels (left), rods (middle) or slits (right) oriented in the x (shown), y or z axis directions (upper row; $x = 20$ cm, $y = 60$ cm, and $z = 6$ cm) and with cooling channels as pore space of simple cubic SC (left, $\varphi = 0.52$), body centered cubic BCC (middle, $\varphi = 0.68$) and face centered cubic FCC (right, $\varphi = 0.74$) sphere packings (lower row). Gray arrow shows beam direction.