Abstract 011

Thermal modelling of a solid cyclotron target using finite element analysis: An experimental validation

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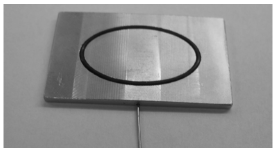
Introduction: Although radioisotope production yields may be increased by elevating the irradiation current, the maximum allowable irradiation current is often dictated by the thermal performance of a target. This limitation is commonly observed for solid targets as these materials often demonstrate poor thermal conductivities and low melting points. As we are interested in improving the power rating of solid targets by optimizing the shape and location of the cooling channels, we have investigated the use of finite element analysis to model both heat transfer and turbulent flow. Before cooling optimization can be performed however, we needed to first validate our initial model. Such an experimental validation is the focus of this work.

Methods: For the purpose of validating the finite element model, we have designed a target plate with a simplistic geometry. In order to perform on-line real-time temperature measurements, this target plate is equipped with a thermocouple that extends to the centre of the plate [upper right]. Target plates of both copper and zirconium were constructed. These materials were selected for their markedly different thermal properties: copper is an excellent thermal conductor with a thermal conductivity, k, of 401 $\text{Wm}^{-1}\text{K}^{-1}$ (@ 300 K), while zirconium is a relatively poor thermal conductor with k equal to 22.6 $\text{Wm}^{-1}\text{K}^{-1}$ (@ 300 K). The target plate and thermocouple were mounted into the water/helium cooled target assembly [lower right]. Irradiations were performed with proton currents up to 80 µA (17.5 MeV) for the copper plate and 50 µA (15.5 MeV) for zirconium. Both the beam tuning[1] and target positioning were optimized to maximize the temperature readout. In calculating the power on the target plate, we have assumed a 10 percent beam loss to the target nosepiece/helium cooling chamber. Several low current measurements were also obtained without helium cooling as this source of cooling is not yet incorporated into the finite element model.



The 3D heat transfer and turbulent flow of the cooling water were modelled using the COMSOL Multiphysics® v. 3.5a. steady-state general heat transfer and k-ε turbulence models, respectively. Experimental input parameters to the model include the cooling water temperature, cooling water flow rate, target plate/cooling water channel geometry, and a sample proton beam profile obtained using radiochromic film[2]. The temperature dependent material properties (i.e. thermal conductivity, density, heat capacity, etc.) were defined using COMSOL's built-in material library.

One of the primary challenges in developing the model was to accurately define the convective heat transfer at the water/plate boundary. Although COMSOL has built-in heat transfer coefficients for various geometrical configurations, at present these coefficients are limited exclusively to air cooling applications. To this end, three user-defined strategies were employed for evaluating the convective heat transfer coefficient at the water/plate interface.

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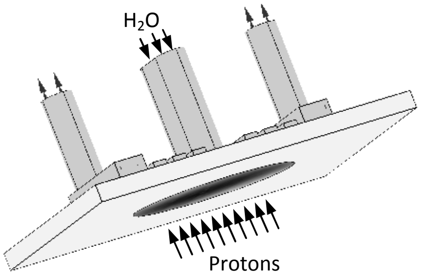
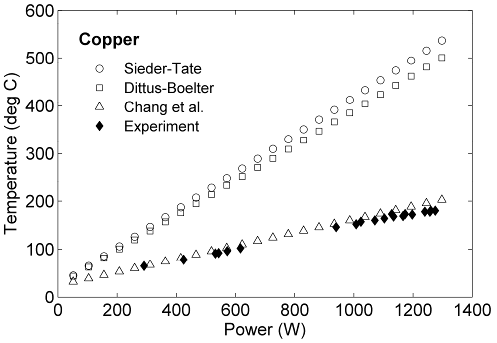
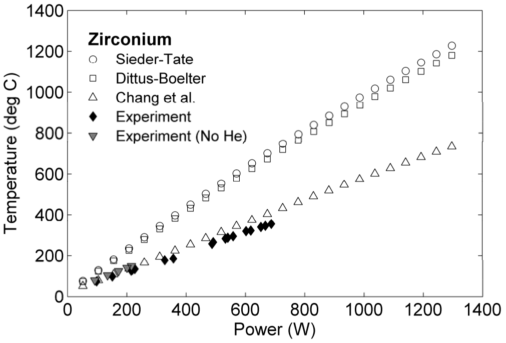
[1] See WTTC13 abstract: J.S. Wilson et al., A Simple Target Modification to Allow for 3-D Beam Tuning

[2] Avila-Rodriguez et al., Appl. Radiat. Isot., 2009, 67: 2025



The cooling geometry under consideration consists of a single central-inlet water-cooling channel and two water-outlets, all of which are perpendicular to the target plate [upper right]. Although the Dittus-Boelter and Sieder-Tate heat transfer formalisms are used to describe turbulent forced convection within long straight pipes (which is not representative of our geometric configuration), these two strategies were nevertheless investigated as both formalisms have been previously implemented and recommended for targetry applications[3,4,5]. The third model employed for evaluating the heat transfer coefficient (selected for its geometric similarity to our configuration) was a method characterized by Chang et al. for turbulent submerged liquid jets[6]. In all three strategies the Reynolds number was calculated from the temperature dependent water properties, the hydraulic diameter of the inlet water-cooling channel and the inlet water velocity, while the Prandtl number was calculated from the temperature dependent water properties. COMSOL's non-linear, direct (UMFPACK) parametric segregated solver was employed to evaluate beam powers ranging from 50–1300 W.





Results: Three models were employed for characterizing the heat transfer at the water/plate boundary. Although all three strategies give rise to heat transfer coefficients whose magnitude increases as the cooling-water flow rate increases, when comparing the model predictions with experimental data [graphs, right], the results of this work suggest that the heat transfer in our geometric configuration is best described by the method proposed by Chang et al[6]. The poor performance of the Dittus-Boelter and Sieder-Tate correlations has been attributed to the underlying geometric assumptions of these models.

Conclusion: The experimental measurements performed in this study have allowed us to select a convective heat transfer model which is capable of accurately predicting the target plate temperature for materials with widely varying thermal properties. Future finite element investigations will include the introduction of helium cooling and the optimization of the cooling channel geometry for the purpose of improving the solid target power rating.

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[3] Pavan et al., J. Radioanal. Nucl. Chem., 2003, 257: 203

[4] Avila-Rodriguez et al., Proceedings of the COMSOL Conference, 2007, 359.

[5] IAEA Technical Reports Series no. 465, Vienna, 2008

[6] Chang et al., Int. J. Heat Mass Transfer, 1995, 38: 833