Scholarly Research Exchange

Volume 2009 • Article ID 608735 • doi:10.3814/2009/608735

Research Article

Thermal Management of Wide-Beam Area X-Ray Sources

Nicolae A. Bobolea, J. Michael Doster, and Mohamed A. Bourham

Department of Nuclear Engineering, College of Engineering, North Carolina State University, Raleigh, NC 27695-7909, USA

Correspondence should be addressed to Nicolae A. Bobolea, alinbobolea@yahoo.com

Received 14 April 2009; Revised 22 July 2009; Accepted 9 August 2009

A wide-beam area X-ray source has been envisioned as capable of delivering X-ray radiation similar to a synchrotron source in terms of the magnitude of photon flux, energy range, and collimation for clinical Diffraction Enhanced Imaging (DEI) applications. Since most of the electron beam energy used to generate the X-rays is deposited in the target material as heat, a cooling system which ensures adequate thermal management is critical to the design. Previous work has shown the feasibility of a prototype scale target with heat fluxes equivalent to those envisioned for an industrial scale system. In this study, a cooling system for an industrial scale target is proposed which is capable of handling a maximum uniform heat flux of 11.693×10^6 W/m^2 for a total thermal loading of 180 kW (3 Amp beam current at 60 kV accelerating voltage). The target behavior was simulated using the CFD code, ANSYS CFX. The simulation results show that target integrity can be maintained for highly non uniform heat fluxes with moderate coolant velocities and pumping powers.

1. Introduction

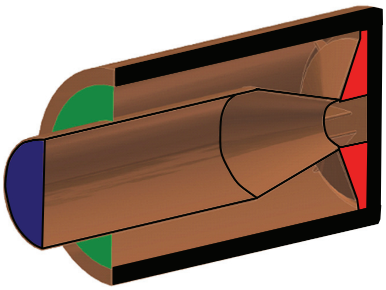
Diffractional Enhanced Imaging (DEI) using X-ray radiation has shown potential for digital mammography and other medical applications as it provides better image contrast at lower radiation dose as compared to conventional X-ray systems [1]. The well-collimated, high-intensity photon flux required for DEI applications is usually obtained from a synchrotron source. Due to the cost and size of such installations, its practical deployment in the vicinity of medical facilities is not considered feasible. Consequently, wide-area X-ray sources based on electron bombardment of suitable target materials have been proposed as an alternative to synchrotron sources for the production of the required photon flux [1–4]. Since the X-ray production efficiency is low, most of the electron beam energy is transferred to the target as heat. Operation at commercial levels requires an electron beam current of 3 A and a 60 kV acceleration potential which impose a total power of 180 kW on the target [1]. The proposed target area for commercial scale systems is 15393.8 mm^2 with an associated heat flux of 11.693×10^6 W/m^2 [5]. An adequate thermal management solution capable of removing the thermal load, maintaining target integrity, and ensuring safe operation during the scanning time is therefore required. In this work, electron backscattering from the target is neglected leading to a conservative thermal design. In addition, structural issues associated with target operation are not considered.

Previous work on a prototype proof-of-principle design considered a cooling solution based on an inner impinging jet using room temperature water at atmospheric pressure as coolant [1, 6]. The proof-of-principle design was a factor of twenty three smaller in illuminated surface area but maintained the same surface heat flux as the proposed commercial scale target. Simulation results showed that jet cooling provided good heat rejection capabilities for a uniform heat flux distribution on the target provided that coolant inlet velocities are higher than 2 m/s.

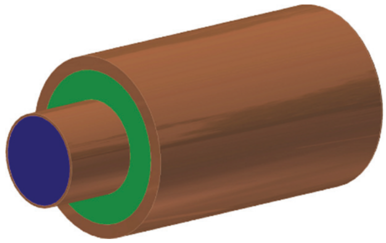
In the current study, a cooling solution based on scale-up of the proof-of-principle design is investigated through simulation using ANSYS-CFX [7]. The results of this investigation have lead to the development of an alternate target design for a commercial scale target which replaces the inner jet cooling with a cooling system design incorporating coolant channels running parallel to the target back.

2. Scale-Up of Proof-of-Principle Target Design

Due to the success of jet cooling for the proto-type, it was the first option investigated as the target heat removal solution



(a) Fins and flow channels



(b) Complete design

Figure 1: Full-scale jet cooling target design.

Table 1: Full-scale jet cooling target design parameters.

Parameter	Value
Inlet diameter (mm)	68.0
Nozzle diameter (mm)	28.8
Outlet area (mm^2)	6625.6
Heated target diameter (mm)	132.4
Target thickness (mm)	10.8

for the commercial scale design [5]. Although jet cooling was ultimately rejected as the final design solution for the commercial scale system in favor of the design presented later in this paper, performance of the jet cooling design is presented here for completeness. For the scaled up proof of principal design, the target diameter was increased by a factor of 4.74 above that of the prototype. Additionally, fins (red surface) were added on the back of the target to provide a uniform coolant distribution and enhance the heat transfer. Figure 1 presents the target design for the scaled up jet cooling system, where a vertical crossing section is shown in Figures 1(a) and 1(b) shows the assembled target.

The coolant (water) enters through the central pipe (blue surface) is accelerated through the jet (black) flows through the channels on the back of the target and returns to the exit (green surface). Initially, the target was to be constructed entirely of copper to take advantage of copper's high thermal conductivity, and to employ a thin Molybdenum layer on the target face for X-ray production. For the purposes of this analysis, the thin molybdenum layer is not modeled and the target is considered entirely from copper. The copper properties are taken from the ANSYS material database and are independent of temperature. The dimensions of the target are provided in Table 1.

Simulations of target performance were performed using the Computational Fluid Dynamics (CFD) code ANSYS CFX which allows for coupled heat transfer and fluid flow calculations within the target and the target structure. The design geometry was created with Autodesk Inventor while the input mesh file for the ANSYS CFX model was generated by the meshing tool ICEM CFD [8]. Flow turbulence was determined by the k-ε turbulence model [9–11].

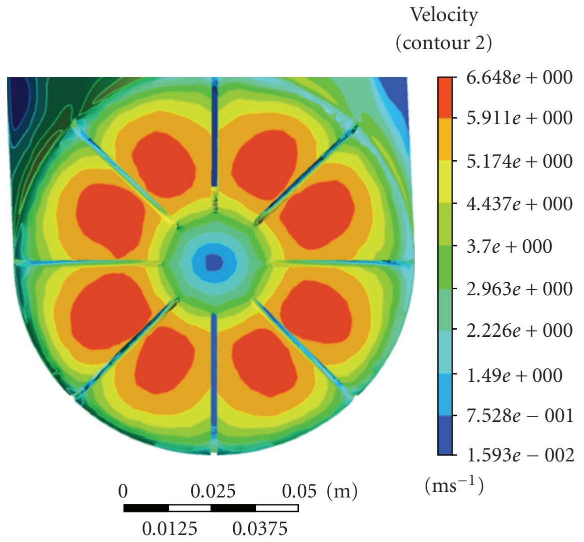
Evaluation of this design has been performed for normal inlet water velocities of 1, 2, and 3 m/s, which give mass flow rates of 3.6 kg/s, 7.2 kg/s, and 10.8 kg/s. The inlet water temperature is 293 K. A uniform heat flux equivalent to a power level of 180 kW was imposed. No heat losses through radiation from the target to the surroundings are considered.

Simulation results have shown that the maximum target temperature is 1223.0 K which corresponds to an inlet water velocity of 1 m/s. Although the maximum temperature is less than the melting point of copper (1356 K), little margin is left to accommodate heat flux nonuniformities which are inevitable from any realistic distributed electron beam on the target surface. The coolant temperature increase from the inlet to the outlet is 11.8 K, 5.9 K, and 3.9 K for 1, 2, and 3 m/s. An increase in inlet velocity results in a decrease of maximum target temperature to a minimum of 939.8 K, while the pumping power necessary to provide forced coolant flow increases substantially with increasing inlet velocity up to a maximum of 1372.5 W (1.8 hp). The temperature distribution on the target is presented in Figure 2 (b). The location of the maximum target temperature is at the center of the target. This is a direct result of a flow stagnation point which develops on the back of the target, as seen in Figure 2. Additionally, a low-pressure region establishes under the jet top wall which, coupled with high water temperature, may cause localized boiling to occur.

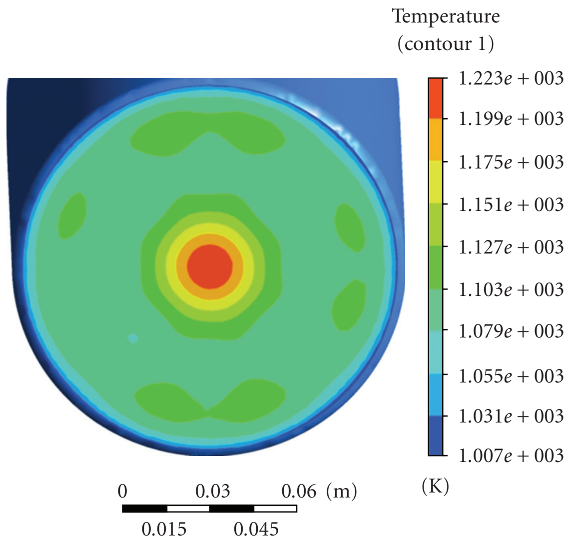
It can be observed from Figure 2(a) that high-velocity water flow parallel to the back of the target ensures adequate cooling and prevents the appearance of temperature hot spots on the target. This also minimizes the pressure losses associated with flow and positively impacts the pumping power. Moreover, reducing the thermal resistance of the target by making the target thinner will increase the heat transfer by conduction and reduce the target temperature. These observations were the basis for subsequent refinements and improvements which led to the development of the final commercial scale design.

3. Commercial Scale Target Design

Continuous improvements of the target cooling system based on simulation results for the scaled-up proof-of-principle design ultimately resulted in abandonment of the jet cooling design in favor of a design incorporating coolant channels running parallel to the target back [5]. The main requirements for the commercial scale design are (1) to limit the maximum target temperature to values significantly less than the melting point of the target material, (2) to minimize the pumping power associated with the coolant flow through the target, (3) to maintain single phase forced convection as



(a) Coolant velocity at coolant-target interface



(b) Target temperature distribution

Figure 2: Simulation results.

the heat transfer mechanism of choice between the target and the coolant, and (4) to maximize the peak to average ratio that the target can withstand under a nonuniform heat flux distribution. Single phase forced convection is preferred due to ANSYS CFX lack of capability to simulate two phase flow.

3.1. Design Description. The commercial scale design uses a thin circular target to generate the high-intensity photon flux required by DEI applications. The heat is removed from the target by flowing high-velocity water through channels positioned horizontally on the back of the target. The channels are enclosed in a water box. The walls of the flow channels also serve as heat dissipating fins. A circular inlet duct with gradually decreasing flow area evenly distributes the flow and accelerates the fluid prior to entering the channels. After the water passes over the back of the target, it is discharged through a circular outlet duct. The outlet duct has a flow area smaller than the inlet duct to prevent vortex formation near the exit. The target is constructed entirely of molybdenum since it generates X-rays with the energy (18 keV) recommended for mammography investigation [1]. Although molybdenum has a smaller thermal conductivity than copper, its melting point is far superior and the conduction resistance can be reduced by minimizing the target thickness. To satisfy the melting point constraint, the maximum allowable molybdenum target temperature must be less than 2890 K. Molybdenum properties are assumed independent of temperature and are defined by the user in ANSYS based on the data available from [12].

The commercial scale design comes in three distinct versions which differ only in the total target wall thickness (1.2, 1.4, and 1.6 mm). The geometry features of the final design are presented in Table 2, Figures 3 and 4.

Table 2: Commercial scale target design geometry.

Parameter	Value
Inlet area (mm^2)	15393.8
Outlet area (mm^2)	3848.45
Fin thickness (mm)	2.0
Fin height (mm)	16.0
Fin length (mm)	160.0
Water box wall thickness (mm)	1.0
Cooling channel height (mm)	16.0
Cooling channel width (mm)	8.0
Heated target diameter (mm)	140.0
Heated target area (mm^2)	15393.8
Target wall thickness (mm)	0.2/0.4/0.6
Total target thickness (mm)	1.2/1.4/1.6

3.2. Design Evaluation. Final target design performance has been assessed using ANSYS CFX. For each of the three final design versions, a geometry file was constructed in Autodesk Inventor and a mesh file was generated by ICEM CFD. A total of 21 CFD models have been developed to fully assess the final design performance. The turbulence model used in the simulations was the k-ε model [9–11].

The inlet water velocity has been varied from 0.6 m/s to 1.2 m/s in increments of 0.1 m/s and a constant inlet water temperature of 293 K was assumed. No heat losses through radiation from the target to the surroundings are considered.

Uniform and nonuniform heat flux distributions have been imposed as boundary conditions on the heated target surface for each combination of wall thickness and water inlet velocity. The uniform heat flux is based on the assumption of uniform electron distribution on the target for a maximum target power of 180 kW. For a target area of 15393.8 mm^2, this yields a uniform heat flux of 11.693×10^6 W/m^2.

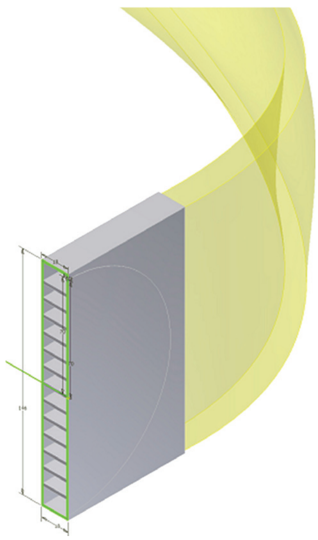


FIGURE 3: Commercial scale target design—sectional view.

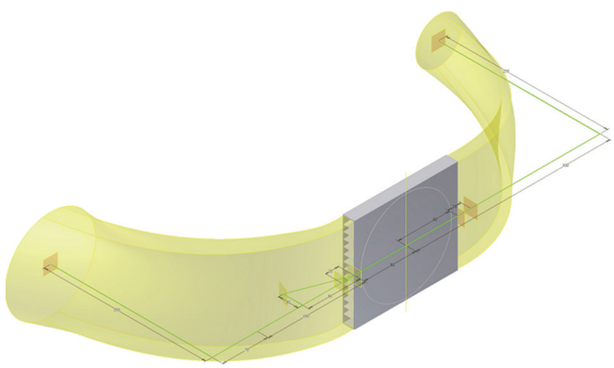


FIGURE 4: Commercial scale target design—full view.

The nonuniform heat flux distribution was generated based on the normal distribution:

$$f(x, \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2} \qquad (1)$$

In (1), x is the function argument, μ is the expected value (mean) and σ represents the standard deviation.

The normal distribution was translated into a 3D heat flux shape for which a specified peak to average ratio can be set by adjusting the normal distribution standard deviation. By setting the normal distribution mean to zero, the heat flux shapes are symmetric over the origin and the target center is the most limiting position for the maximum heat flux. Figure 5 present a heat flux shape with a peak to average ratio of 4.37.

For the uniform heat flux distribution, the goal is to determine the dependence of maximum target temperature and pumping power on total target thickness and inlet water velocity. For nonuniform heat flux distributions, the peak to average ratio which leads to either coolant boiling or the target melting temperature has been determined as a function of the same parameters.

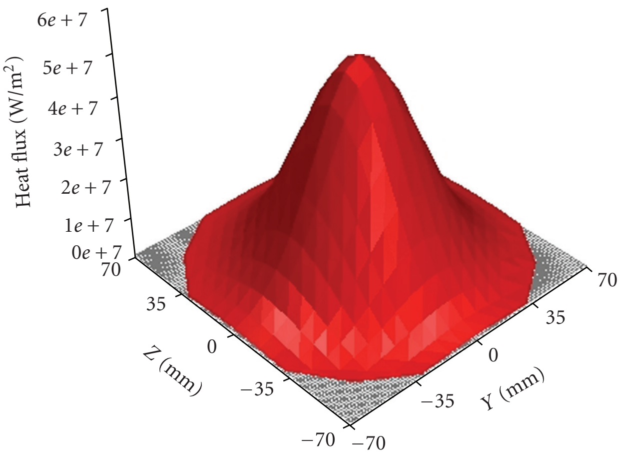


FIGURE 5: Heat flux shape with peak to average ratio of 4.37.

TABLE 3: Maximum target temperature simulation results for uniform heat flux distribution, K.

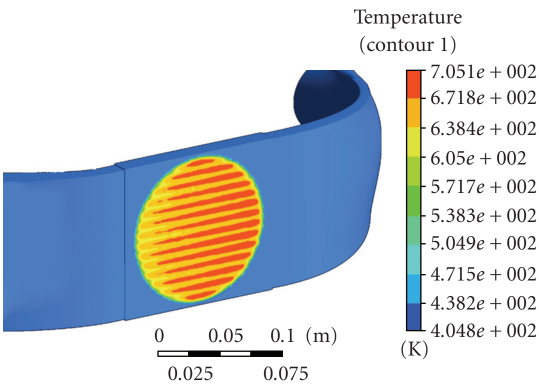
Water inlet velocity (m/s)	Total target thickness (mm)		
	1.2	1.4	1.6
0.6	801.4	817.3	829.2
0.7	754.9	771.1	784.0
0.8	718.3	734.7	748.3
0.9	688.6	705.2	719.3
1.0	664.0	680.7	695.3
1.1	643.3	660.1	675.0
1.2	625.5	642.5	657.7

3.3. Simulation Results. The simulation results for maximum target temperature are presented in Table 3. It can be seen that, for a uniform heat flux distribution, the temperature ranges between 625.5 K and 829.2 K. These values are significantly less that the molybdenum melting point of 2890 K. Figure 6(a) presents target temperature distribution for the commercial scale target design with a thickness of 1.4 mm, water inlet velocity of 0.9 m/s, and uniform heat flux distribution, while Figure 6(b) showing the target temperature distribution for the commercial scale target design for the same design and operating parameters except the heat flux distribution is nonuniform with a peak to average ratio of 5.79.

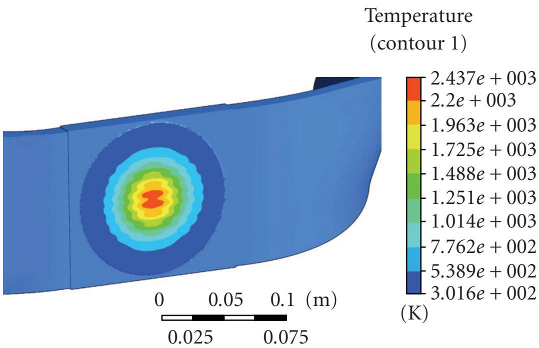
A graphical representation of normalized maximum target temperature obtained by dividing all the values by the maximum value for data in Table 3 is provided in Figure 7.

Table 4 presents the simulation results for pumping power. As can be seen, adequate target cooling requires reasonable pumping power. Figure 8 provides a visual representation of normalized pumping power.

The results for the evaluation of peak to average ratio are presented in Table 5. It is worth noting that the final target design is capable of withstanding significant nonuniformities in heat flux.



(a) Uniform heat flux distribution



(b) Nonuniform heat flux distribution

FIGURE 6: Target temperature distribution.

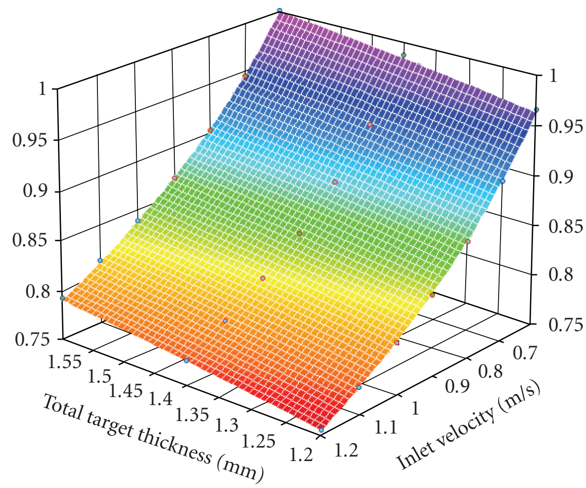


FIGURE 7: Normalized maximum target temperature.

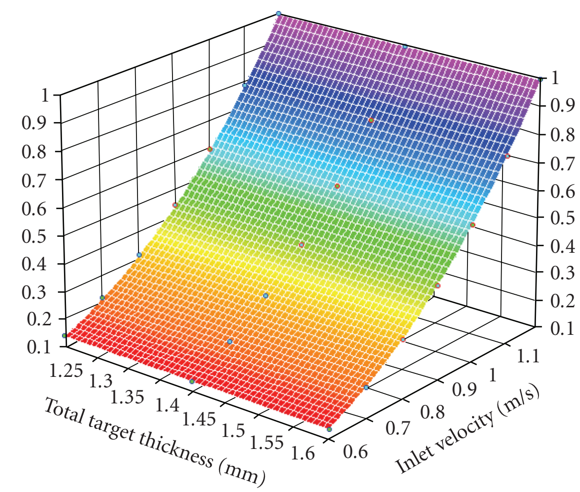


FIGURE 8: Normalized pumping power.

TABLE 4: Pumping power simulation results, W, (hp).

Water inlet velocity (m/s)	Total target thickness (mm)		
	1.2	1.4	1.6
0.6	85.4 (0.1)	84.9 (0.1)	84.8 (0.1)
0.7	132.3 (0.2)	131.4 (0.2)	131.3 (0.2)
0.8	193.6 (0.3)	192.2 (0.3)	192.1 (0.3)
0.9	271.0 (0.4)	269.1 (0.4)	268.9 (0.4)
1.0	366.5 (0.5)	364.0 (0.5)	363.6 (0.5)
1.1	481.9 (0.6)	478.5 (0.6)	478.1 (0.6)
1.2	619.0 (0.8)	614.7 (0.8)	614.2 (0.8)

TABLE 5: Peak to average ratio simulation results.

Water inlet velocity (m/s)	Total target thickness (mm)		
	1.2	1.4	1.6
0.6	4.4	3.6	3.6
0.7	5.4	4.3	4.4
0.8	6.4	5.0	5.2
0.9	7.5	5.8	6.1
1.0	8.1	6.6	7.0
1.1	8.6	7.4	7.7
1.2	9.0	8.2	8.1

The normalized dependence of peak to average ratio as a function of target thickness and water inlet velocity is depicted in Figure 9.

A complete image of final target design performance can be constructed by plotting the normalized maximum target temperature (red), pumping power (blue), and peak to average ratio (green) on the same graph, as seen in Figure 10. This representation shows that the design ensures reasonable target temperatures and, at the same time, large nonuniformities in the heat flux shape can be accommodated. Higher peak to average ratios require higher pumping power to maintain the integrity and safe operation of the target. Limiting these parameters to lower values can be achieved through a target illumination which generates a flattened heat flux profile. Such a flattened heat flux may be achieved by careful design of the electron beam generation system and its geometry.

3.4. Result Analysis. To gain further insight into the simulation results, graphical representations have been developed

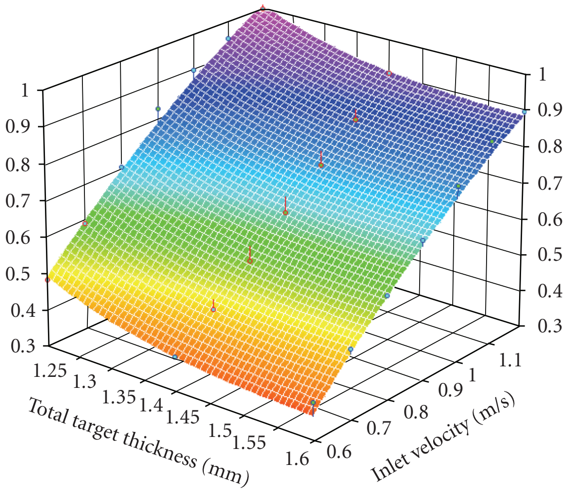


Figure 9: Normalized peak to average ratio.

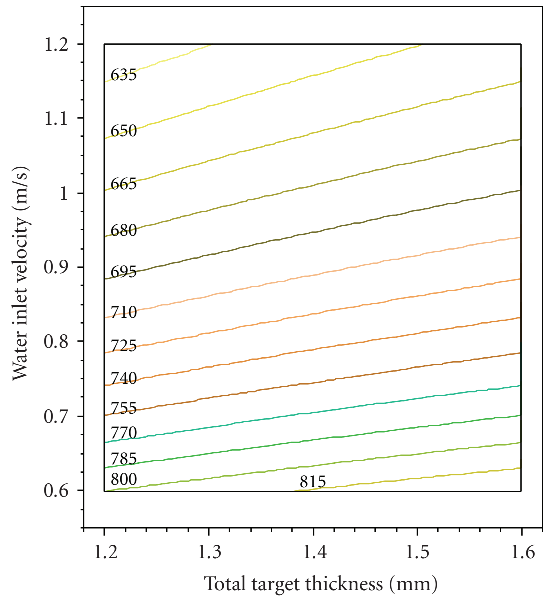


Figure 11: Maximum target temperature contour plot, K.

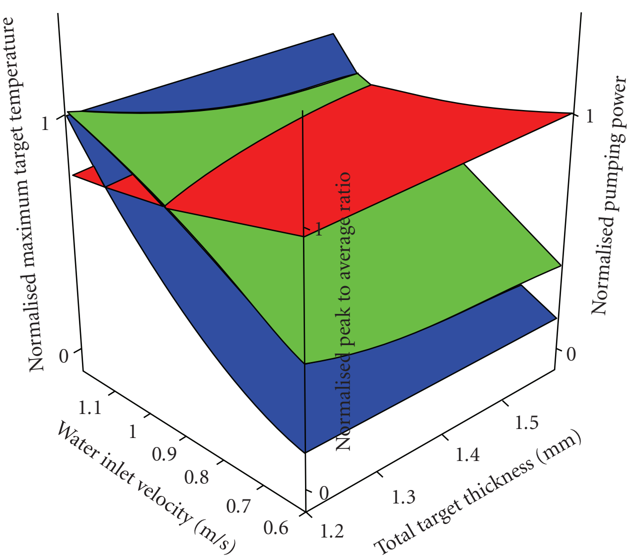


Figure 10: Integrated final target design performance.

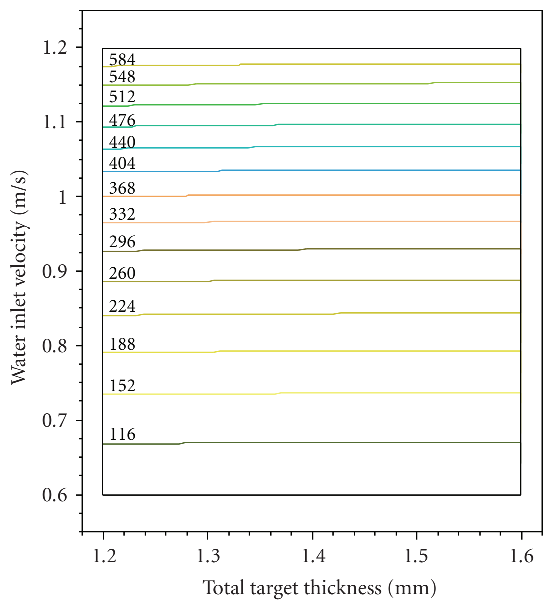


Figure 12: Pumping power contour plot, W.

in the form of contour plots. The contour plots not only provide numerical evaluation of maximum target temperature, pumping power and peak to average ratio, but also show their dependence on design and operating parameters. The maximum target temperature contour based on a uniform heat flux distribution is presented in Figure 11.

Figure 11 shows that maximum target temperature increases linearly with target thickness and decreases with inlet water temperature. Increasing the water velocity enhances the heat transfer through convection which causes the target temperature to drop. On the other hand, a thicker target increases the thermal resistance, decreases heat transfer through conduction and makes the target temperature higher. The contour plot lines are constant temperature lines and allow a rapid evaluation of target temperature. For example, the maximum target temperature corresponding to a target thickness of 1.3 mm and an inlet water velocity of 0.8 m/s is 725 K. If the combination of parameters does not fall on an isotherm, interpolation can be used to determine the desired value.

A contour plot has also been developed for the dependence of pumping power on target thickness and inlet water velocity. It can be seen from Figure 12 that the pumping power increases with increasing water inlet velocity and is

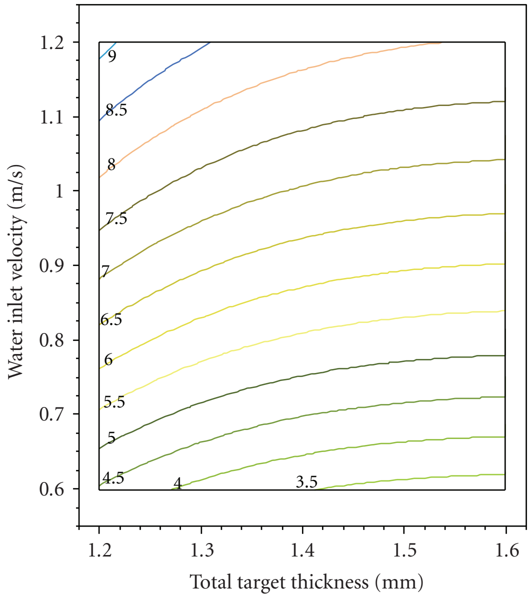


FIGURE 13: Peak to average ratio contour plot.

independent of total target thickness. Although pumping power changes slightly with total target thickness for a constant inlet velocity, these changes are attributed to differences between the final design meshes.

The peak to average ratio contour is presented in Figure 13. The limiting peak to average ratio decreases with increasing target thickness as a consequence of increasing heat conduction resistance. Higher inlet water velocity enhances the forced convection providing a better target cooling. Thus, higher peak to average ratios can be successfully managed.

4. Conclusions

Thermal management of wide beam area X-ray sources poses serious challenges compared to cooling requirements of conventional X-ray sources. Cooling system designs based on impinging water jets have been shown feasible for prototype scale systems, but are nonoptimal when applied to proposed commercial scale systems, mainly due to flow stagnation which yields hot spots in the target center and significantly limits potential nonuniformities in heat flux the target is capable to sustain.

This has led to a cooling system design based on parallel flow channels on the target back. Final design performance has been assessed through steady state simulation under uniform and nonuniform heat flux distributions for a molybdenum target body. The results have shown that the maximum target temperature is substantially less than the molybdenum melting point, for reasonable coolant pumping powers and velocities, and high heat flux peak to average ratios can be tolerated without compromising target operation. CFD simulations of the final design using ANSYS CFX have shown that sustainable operation can be achieved at commercial levels while meeting the design requirements.

References

[1] C. H. Kim, *A study of monochromatic X-ray area beam for application in diffraction enhanced imaging*, Ph.D. dissertation, North Carolina State University, Raleigh, NC, USA, 2007.

[2] E. Pisano, E. Johnson, D. Chapman, et al., "Clinical diffraction enhanced mammography unit," NCSU and UNC-CH, Invention Disclosure, July 2000.

[3] E. D. Pisano, D. Chapman, D. Sayers, et al., "Design of a clinical diffraction enhanced imaging unit for breast imaging," in *Proceedings of the16th Annual Radiology Research Symposium*, University of North Carolina, March 2001.

[4] E. D. Pisano, D. Chapman, D. Sayers, et al., "Diffraction enhanced imaging (DEI) of human breast cancer specimens," in *Proceedings of the 16th Annual Radiology Research Symposium*, University of North Carolina Chapel Hill, March 2001.

[5] N. A. Bobolea, *Thermal design of wide beam area x-ray sources*, M.S. thesis, North Carolina State University, Raleigh, NC, USA, 2009.

[6] C. H. Kim, J. M. Doster, and M. A. Bourham, "Wide-beam x-ray source target thermal management simulation using inner jet cooling," *Scholarly Research Exchange*, 2009.

[7] ANSYS Inc., "User manual," ANSYS CFX Release 11.0, 2006.

[8] ANSYS Inc., "User manual," ANSYS ICEM CFD/AI Environment Release 11.0, 2007.

[9] ANSYS Inc., "ANSYS CFX-solver theory guide," ANSYS CFX Release 11.0, 2006.

[10] H. Tennekes and J. L. Lumley, *A First Course in Turbulence*, MIT Press, Cambridge, Mass, USA, 1972.

[11] D. C. Wilcox, *Turbulence Modeling for CFD*, DCW Industries Inc., 1994.

[12] MatWeb, "100% pure Molybdenum annealed data sheet," Marketech International Inc.