DESIGN AND THERMAL ASPECTS OF WATER COOLED PRIMARY MIRROR FOR SYNCHROTRON RADIATION

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ABSTRACT

This paper describes the thermal analysis of water cooled primary mirror used in BL-23 of Indus-2 at RRCAT in which the mirror thermal deformation was minimized for acceptable optical performance. The primary mirror separates the visible part from synchrotron radiation by reflecting visible part to perpendicular plane. In worst condition the primary mirror will be subjected to intense heat load of 150 W, primarily due to X-Ray absorption. This intense heat load will distort the reflecting surface. So couple-field thermo-structural numerical simulations was carried out using ANSYS, to decide effective cooling scheme and optimum cooling parameter such as number of cooling channel, diameter of cooling channel, position of cooling channels, discharge rate of coolant, in such a way that deformation of reflecting surface of primary mirror was maintained between 20-30 µm for reliable imaging. Since primary mirror system will operate in ultra high vacuum condition, leak testing of brazed joints involved in primary mirror system is also carried out.

Keywords: Thermal Analysis, Synchrotron Radiation, ANSYS, Ultra High Vacuum, Primary Mirror System.

1. INTRODUCTION

Synchrotron radiation (SR) is emitted by the relativistic electron when it undergoes bending in dipole magnet. The spectrum of SR coming out of source ranges from infrared to hard X-rays. A beam line is needed to guide synchrotron radiation from source to experimental station [1, 2]. Beam line has many optical and mechanical subsystems. Primary mirror (PM) is one of the opto-mechanical subsystems which are used in beamline 23 (BL-23). PM is a metallic mirror placed in such a way that it reflects visible part of synchrotron radiation, which is coming out horizontally from bending magnet, in vertically upward direction. However, other components of SR like X-Rays, Infra-Red and ultraviolet get deposited on primary mirror (refer to Fig 1).
The photons of these components deposit their energy in the form of heat which gives rise to thermal deformation of reflecting surface of mirror and hence cause the image distortion [3, 4, 5] and PM will operate in ultra high vacuum (UHV) condition, so special care need to be taken in material selection and joints involved.

The primary objective of this paper is to discuss material selection, coupled thermal and structural analysis [6] of primary mirror using finite element method to study the effect of flow and geometric parameter such as position of cooling channel, diameter of cooling channel, and flow-rate on the deformation of the reflecting surface and leak testing of fabricated primary mirror system with recommendation of thermal analysis.

2. DESIGN ASPECTS

Primary mirror is a crucial component of visible diagnostic beam line. There are many design constraints which govern the performance of primary mirror but the intense continuous heat-load in form of SR is the most important design constraint. Other design constraints are as follows.
3. PRIMARY MIRROR THERMAL LOADING

For Indus-2 having energy 2.5 GeV, current 300 mA and radius of curvature of bending magnet 5.5m, the total radiated power in one revolution is 186 KW, which gives approximately 30W per mrad. Visible diagnostic beam line has 7mrad opening angle (along the x-axis). With this opening angle there is total heat load of 210 W deposited on the shaded area of reflecting surface (refer Fig 3). Its dimension in projected plane normal to beam axis is 35 mm (±17.5 mm about centre) × 54mm.

3.1 Finite element modelling

Photons deposits their energy in the bulk of mirror substrate and results in volumetric heat generation. However, to model worst condition it can assume that photon deposits their energy on the reflecting surface. Without loss of generality one can assume that reflecting surface is exposed to heat flux numerically equivalent to deposited energy by photon per unit area of reflecting surface. Primary mirror is descritzed using PLANE55 element, which is a plane element with a two-dimensional thermal conduction capability. The element has four nodes with a single degree of freedom, temperature, at each node.
Heat transfer coefficient was calculated using Dittus and Boelter correlation

\[ \text{Nu} = 0.026(\text{Re}^{0.8})(\text{Pr}^{0.3}) \text{ for cooling } 5 \leq \text{Pr} \leq 3 \text{ and } 10^4 \leq \text{Re} \leq 10^6 \]  

(1)

Following assumptions were made in the modelling the primary mirror:

1. Heat flux follows the Poisson distribution along Y-axis but we assumed uniform heat flux of 0.06 W/mm²-K.
2. Heat loss by conduction through the supports of primary mirror, natural convection and through radiation is neglected.
3. Material properties such as specific heat, conductivity and viscosity are considered to be independent of temperature and their values are taken at room temperature.

3.1.1 Boundary conditions
1. For structural analysis the bottom portion of mirror is assumed to be fixed.
2. For thermal analysis the irradiated surface is assumed to have heat flux of 0.06 W/mm²-K.
3. For thermal analysis the coolant channel surfaces are assumed to be having constant value of heat transfer coefficient.

3.1.2 Parameter which affect the thermal deformation of reflecting surface

1. Flow parameter
   a. Inlet temperature of coolant
   b. coolant flow velocity

2. Geometrical properties
   a. Diameter of cooling channel.
   b. Normal distance of axis of cooling channel from reflecting surface.
   c. Number of cooling channels.

3.1.3 Limitation on the parameters
1. Diameter of cooling channel can be 4.4 mm, 6 mm, 10 mm.
2. Inlet temperature can be between 10°C to 40°C.
3. Discharge is given as 2 liters/min, so velocity can take only limited values based on the assumed diameter of coolant channel.

4. RESULT AND DISCUSSION

A Steady, two dimensional finite element model was developed using ANSYS [9]. Initial temperature of Primary mirror and inlet temperature of coolant was taken 300 °K for all analysis. The number of cooling channels was kept two in all analysis because of manufacturing constraints. The analysis was done in two cases. In first case the distance between the axes of coolant channel was kept constant and normal distance of axes of coolant from reflecting surface was varied. In second case the distance between the axes of coolant channel is varied, keeping normal distance of axes of coolant from reflecting surface constant.

Case1: The distance between the axes of coolant channel was kept constant and normal distance of axes of coolant from reflecting surface was varied for various diameter of cooling channel.
Fig 4: Variation in the deformation of heating surface as axis of cooling channel is moved away from surface for various diameter of cooling channel

1. Red line at 20µm and 30 µm shows the acceptable range of deformations, for 6 mm diameter of cooling channel the normal distance of axes of cooling channel should be kept between 5.5mm to 7.5 mm and for 4mm diameter of cooling channel it should be kept between 4.5mm to 8mm to limit the deformation of heating surfaces between 20-30 µm.
2. As the diameter of coolant channel decreases the deformation of heating surface decreases for same distance of axis of cooling channel from heating surface.
3. Slope of curve decreases as the diameter of cooling channel is decreased i.e. the rate of increase in deformation as the axis of cooling channel move away from heating surface is decreased.
4. With above observation the 4 mm diameter cooling channel with 4.5 mm distance from the heating surface should be used.

Case 2: Distance between the axes of coolant channel is varied for different diameter of coolant channel keeping the normal distance of axis of coolant channel from the heating surface equals to 8.75 mm.

Fig 5: Variation in the deformation of heating surface as the distance between the axes of coolant channel is varied for different diameter of cooling channel keeping normal distance from heating surface equals to 8.75mm
1. As the diameter of cooling channel decreases the deformation of heating surface reduces for given normal distance of axis of coolant channel from heating surface.

2. As observed in Fig 5 the curves are almost straight line, this shows the distance between the axes of coolant has little effect on the deformation of heating surface.

![Fig 6: Effect on the Temperature distribution across the primary mirror with varying distance between the axis of coolant channel for 6mm diameter cooling channel](image)
Referring to Fig 6 it can be seen that

1. As the distance between the axes of coolant channel was decreased the maximum temperature rise initially decreases then increases.
2. As the distance between axes of coolant channel was decreased the maximum temperature rise zone spread along the heating surface and it gets narrow through the thickness of mirror substrate.
3. As the distance between the axes of coolant channel is reduced the temperature gradient along the heating surface decreases and temperature gradient through the thickness of mirror substrate increases, these two factors cancel each other and hence varying distance between axes of coolant has very little effect on deformation of heating surface.

4.1 Leak Testing of Primary mirror mount

![Fig 7: Primary Mirror mount](image)

The whole primary mirror system will operate in UHV condition so the brazing joint between Cu tube & SS316L flange of the primary mirror mount need to be check for leak before welding with bellow because after welding if there will be any leak found during leak testing then the whole assembly will not be able to use in the beam line. For the leak testing of this joint, an extra chamber (this chamber is already qualified in 10-10mbar-l/sec leak rate), an Al flange with centre hole to allow Cu tubes to insert in the chamber.

![Fig 8: Al flange & Back side of mirror mount flange](image)
The mirror mount flange has tapped hole on its back face due to this reason a O-ring of 35mm diameter is used to provide sealing. The O-ring was compressed between Al flange & mirror mount flange and provides sealing.

![Image of assembly](image1.png)

**Fig 9:** Assembly of primary mirror mount with Chamber for leak testing

As shown in the Fig 9 different mild steel blocks, C clamps along with studs were used to assemble mirror mount with chamber and Al flange.

In order to leak testing of the brazing joint Outside-in method of Helium leak testing method was used and the chamber was connected to Mass Spectrometer Leak Detector (MSLD) and evacuated after that He gas was sprayed on the brazing joint and tested for leak. The joint has qualified in $10^{-10}$ mbar-l/sec order of leak rate.

![Image of welded assembly](image2.png)

**Fig 10:** Welded assembly of Mirror mounts with bellow
5. CONCLUSION

The parametric study was done with two cooling channel and keeping coolant inlet temperature 300°C. Following conclusions were made based on the observations of analysis.

1. Using 10mm diameter cooling channel the flatness of cooling channel cannot be achieved between 20-30µm with any combination of normal distance of axes coolant channel from heating surface and distance between the axes of cooling channel.

2. Using 6 mm diameter cooling channel, if normal distance of axes coolant channel from heating surface is equal to or less than 7.5 mm with any combination of distance between the axes of coolant channel the flatness of heating can achieved between 20-30µm.

3. Using 4 mm diameter cooling channel, if normal distance of axes coolant channel from heating surface is equal to or less than 8mm with any combination of distance between the axes of coolant channel the flatness of heating can achieved between 20-30µm.

4. The primary mirror system was fabricated with cooling channel of 4mm diameter and distance of its axis from reflecting surface equals to 5mm. The fabricated system was leak test and qualified in 10^{-10} mbar-l/sec order of leak rate.

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