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The Cryogenic Cooling Program in High-Heat Load Optics at the Advanced Photon Source.*

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C.S. Rogers
Experimental Facilities Division
Advanced Photon Source
Argonne National Laboratory
Argonne IL 60439

July, 1993

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*This work supported by the U.S. Department of Energy, BES-Materials Sciences, under contract no. W-31-109-ENG-38

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The Cryogenic Cooling Program in High-Heat-Load Optics at the Advanced Photon Source

C. S. Rogers

Argonne National Laboratory
The Advanced Photon Source
Argonne, IL 60439
rogers@oxygen.aps1.anl.gov

ABSTRACT

This paper describes some of the aspects of the cryogenic optics program at the Advanced Photon Source (APS). A liquid-nitrogen-cooled, high-vacuum, double crystal monochromator is being fabricated at Argonne National Laboratory (ANL). A pumping system capable of delivering a variable flow rate of up to 10 gallons per minute of pressurized liquid nitrogen and removing 5 kilowatts of x-ray power is also being constructed. This specialized pumping system and monochromator will be used to test the viability of cryogenically cooled, high-heat-load synchrotron optics. It has been determined that heat transfer enhancement will be required for optics used with APS insertion devices. An analysis of a porous-matrix-enhanced monochromator crystal is presented. For the particular case investigated, a heat transfer enhancement factor of 5 to 6 was calculated.

NOMENCLATURE

A_H = Total convective heat transfer area

$C_{p,f}$ = Fluid specific heat at constant pressure

d = Channel diameter

d_w = Screen wire diameter

EF = Enhancement factor

h_w = Heat transfer coefficient of screen mesh wire

k_f = Fluid thermal conductivity

k_w = Screen material thermal conductivity

L = Length of channel

$\dot{m}$ = Mass flow rate

N_{tu} = Number of transfer units for enhanced heat exchanger

N'_{tu} = Number of transfer units for unenhanced heat exchanger

Pr = Prandtl number

Q = Heat transfer rate of enhanced heat exchanger

q = Heat transfer rate of unenhanced heat exchanger

Re = Approach Reynolds number = $\rho v d / \mu$

Re_l = Local Reynolds number = $\rho v_l d / \mu_{A_H}$

r_0 = Radius of channel

St = Stanton number

T_s = Surface temperature

$T_{f,i}$ = Fluid inlet temperature

V_H = Total volume of heat exchanger times the porosity

v = Fluid approach velocity

β = Correction factor

η_f = Fin efficiency

μ = Fluid viscosity

σ = Porosity, total volume open to and occupied by fluid

1. INTRODUCTION

The cooling of high-heat-load optics for use at the Advanced Photon Source (APS) is a subject of continuing research. When the APS begins operation in 1996, it will be the world's brightest synchrotron x-ray source. The heat load on the monochromator from APS Undulator A will be nearly 4 kW with a peak power density of 150 W/mm². The incredibly high heat fluxes associated with these beams requires the development of novel approaches to minimize the thermally induced strain in the monochromator crystals. One approach is to maintain the silicon monochromator crystal at cryogenic temperatures. The benefits of the improved thermal characteristics of single crystal silicon at cryogenic temperatures for use in high-heat-load x-ray optics has been recognized for some time.¹ Near 120 K, the linear coefficient of thermal expansion of silicon goes through a zero and the thermal conductivity increases by about a factor of 9 over its room temperature value. These two factors combine to decrease the thermal gradients and strain in the silicon crystal, thereby, preserving the beam brilliance.

The Optics Group of the Experimental Facilities Division at the APS has implemented an aggressive research program to investigate the use of liquid-nitrogen-cooled synchrotron optics. The program consists of analytical and experimental investigations. Finite element analysis is being used to evaluate various cooling geometries for monochromator crystals. The experimental program involves the construction of a high-vacuum double crystal monochromator

and a liquid nitrogen pumping system. This setup will be used to test high performance cryogenic crystals at existing synchrotron facilities and at the APS.

2. EXPERIMENTAL DESCRIPTION

2.1 Liquid Nitrogen Pumping System

The liquid nitrogen pumping system consists of a closed optic loop coupled to an open loop heat exchanger. A flow schematic is shown in Fig. 1. The liquid nitrogen supply to the optic is circulated by a variable-speed, positive-displacement vane pump capable of delivering 0-10 gpm. The system consists of three concentric stainless steel tanks. A static vacuum space exists between the outer and middle tank to provide insulation from the ambient. Located between the middle and inner tank is the primary and secondary heat exchanger. The open-loop liquid-nitrogen bath boils off and removes the optic heat load from the optic loop. The primary heat exchanger is sized to remove up to 5 kW deposited in the liquid nitrogen at the optic. The secondary heat exchanger is placed downstream from the pump to remove the heat added to the nitrogen by the pump itself. The heat exchangers are submersed in a bath of liquid nitrogen at atmospheric pressure. The optic heat load can be increased to 10 kW if the nitrogen bath is operated under vacuum so that it boils at a lower temperature. The bath is automatically maintained at a constant level using a differential pressure controller and a pneumatic cryogenic valve connected to an external storage dewar. The vane pump is located at the bottom of the inner vessel and is submerged in approximately 80 l of liquid nitrogen. The reservoir maintains a positive suction head for the pump while providing a ballast volume of liquid for the closed loop. Additionally, the reservoir acts as a phase separator and allows for changes in system volume due to variations in density of the flowing liquid. The nitrogen flow rate is measured by a cryogenic turbine meter. The nitrogen is conveyed to and from the monochromator by 20-foot-long flexible, vacuum-jacketed lines. A remote panel provides for monitoring the system's operational parameters and control of the flow rate and system pressure.

2.2 Monochromator

A schematic of the vacuum monochromator assembly is shown in Fig. 2. The top and front walls of the vacuum chamber are not shown. The monochromator is a double crystal, two stage arrangement. It is capable of operating in the standard Bragg or the inclined geometry.² The cooled first crystal has two linear degrees of freedom to position it in the beam and a rotational degree of freedom to vary the Bragg angle for both the standard and inclined geometry. The second crystal has three orthogonal linear motions and three rotation axes. Precision control of the Bragg angle on the second crystal is provided by a piezoelectric transducer mounted on a tangent arm. The monochromator is designed to work over the classical energy range of 4 to 20 keV using a Si(111) monochromator with a beam offset of 2.5 to 5 cm.

The monochromator is enclosed within a stainless steel vacuum chamber. All of the step motors and stages operate in a vacuum of approximately 10^{-6} torr. The vacuum is maintained by a turbomolecular pump. Water-cooled inlet and exit beryllium windows mounted on Conflat flanges allow the white beam to pass through the chamber if desired.

Fig. 1 Liquid Nitrogen Pumping System Schematic

Fig. 2 Cryogenic Monochromator

A double block and bleed valve system is provided for coupling the liquid nitrogen from the pumping system into the monochromator. The valve box is coupled to the vacuum tank by a 13.25" Conflat. The nitrogen can be bypassed through this valve array isolating the monochromator so that it can be opened for maintenance or crystal replacement without having to shut down and warm up the entire pumping system. The valve system is also provided for safety so that high pressure nitrogen cannot enter the vacuum chamber when in bypass mode.

3. CRYSTAL DESIGN

Due to the poor transport properties of liquid nitrogen, it is desirable to provide heat transfer enhancement. Several methods have been suggested, such as, microchannels,³ jet impingement⁴, and porous matrices.⁵ The use of microchannels involves the fabrication of very narrow ($O(40 \mu\text{m})$) channels with a high aspect ratio into the monochromator crystal. Even though the flow is laminar, the large thermal conductivity of silicon makes for high fin effectiveness, which increases the heat transfer surface area. Therefore, the total resistance to heat flow is minimized. Several disadvantages exist for microchannels. A cover plate of silicon needs to be bonded to the diffraction crystal to close the channels. It has been our experience that strain-free bonds are

very difficult to fabricate. However, because of the high thermal conductivity, the bond can be far from the diffraction surface minimizing this problem. Additionally, it is very difficult to fabricate the microchannels to the optimum aspect ratio, which is about 35 for a channel width of about 40 μm , for liquid nitrogen.⁶ The pressure drop for microchannels is very high, which limits the length of the channel, makes it difficult to pump the fluid, and may cause flashing of the nitrogen causing the pressure drop to increase exponentially.

The heat transfer coefficient for jet impingement cooling can be much higher than unenhanced forced convection. It has been shown that additional enhancement can be achieved by machining narrow grooves or small studs into the heat transfer surface.⁷ Significant vapor production would likely occur with liquid nitrogen, which may prove difficult to remove rapidly enough. However, it is the author's opinion that cryogenic jet impingement cooling is a promising technique and will be pursued.

The use of the proper porous matrix can avoid many of these difficulties. Porous silicon carbide or beryllium oxide have been suggested for use with single crystal silicon optics.⁵ However, this paper suggests that a copper wire screen porous matrix can be used to enhance the heat transfer of x-ray optics. This method has been successfully applied to front-end components such as the APS photon shutters and fixed masks.^{8,9} The difficulty with porous SiC and BeO, for instance, is that they are very stiff materials, and, because of the mismatch in thermal expansion with silicon, they may introduce strain in the monochromator. However, the copper screen matrix is very compliant, therefore, the expansion mismatch may not strain the crystal. Also, the thermal conductivity of copper is larger than the polycrystalline SiC and BeO. Possible methods of attaching the copper screen plug into a core-drilled channel are brazing or gluing with a thermally conductive adhesive. The advantages of the porous copper matrix are that the effective heat transfer surface area is greatly increased. The heat is conducted more efficiently throughout the volume of the channel. The surface temperatures and heat flux are reduced, which helps alleviate the problem of boiling and critical heat flux. It has been shown that a pin fin surface enhancement displays boiling heat transfer characteristics close to those of a frost-coated surface, which has the highest pool boiling heat flux enhancement.¹⁰ The mesh also mixes the fluid very effectively, thereby, transporting the heat to the central core more rapidly.

3.1 Porous Matrix Enhancement

Qvale and others have proposed an analytical solution for a compact wire screen heat exchanger.^{11,12} For their model, an enhanced tubular heat exchanger is manufactured by inserting a large number of wire screen discs into a tube. The model treats each wire as a pin fin. For a constant surface temperature, the total heat transfer rate is given by

$$Q = h_w \eta_f \frac{A_H}{3\beta} (T_s - T_{f,i}) \left[\frac{1 - e^{-\beta N_{tu}}}{N_{tu}} \right] \quad (1)$$

The heat transfer coefficient at the wire is found from the following expression

$$St Pr^{2/3} = 1.1 \sigma Re_l^{-0.41} \quad (2)$$

Therefore, the heat transfer coefficient at the wire is given by

$$h_w = \frac{1.1 \sigma k_f A_H}{4 V_H} Re_l^{0.59} Pr^{1/3} \quad (3)$$

Utilizing the effectiveness-Ntu method, the number of transfer units for the enhanced heat exchanger is defined by the following equation

$$N_{tu} = \frac{h_w A_H}{\dot{m} C_{p,f}} \quad (4)$$

The correction factor, β , is found using the following equation

$$\eta_f = \frac{\beta(3e^{\beta N_{tu}} - 1)}{e^{\beta N_{tu}} - 1} \quad (5)$$

The fin efficiency is approximated by

$$\eta_f = \frac{\tanh mr_0}{mr_0}, \quad mr_0 = \sqrt{\frac{4h_w}{k_w d_w}} \quad (6)$$

The heat transfer rate for a plain tube with a constant surface temperature is given by

$$q = \dot{m} C_{p,f} (1 - e^{-N_{tu}}) (T_s - T_{f,i}) \quad (7)$$

An enhancement factor can be expressed as the ratio of equations (1) and (7)

$$EF = \frac{\eta_f (1 - e^{-\beta N_{tu}})}{3\beta (1 - e^{-N_{tu}})} \quad (8)$$

Eq. (8) is the ratio of the effectiveness of a porous mesh enhanced heat exchanger to the effectiveness of a unenhanced heat exchanger. The constant correction factor β indicates the effect of the fin efficiency on the fluid temperature.

To investigate the heat transfer enhancement, an example problem is evaluated by analyzing a representative crystal. The example crystal is a block of silicon 2 cm thick, 6 cm long, and 8.6 cm wide. Nine channels have been core-drilled in the lengthwise direction on the central plane. The channels are 1/8" in diameter and spaced 6.1 mm center to center. The enhancement factor as a function of approach Reynolds number is shown in Fig. 3 for an 8x8x0.0126" wire screen mesh and a porosity of 0.75. Note that for this particular case, the maximum enhancement occurs for an approach Reynolds number of about 20,000. At higher Reynolds numbers, the fin efficiency decreases. Also, the heat transfer coefficient of the fin increases at a slower rate than that of a plain tube. Therefore, the enhancement factor drops off with increasing flow. At lower Reynolds numbers, the correction factor β dominates because the temperature rise of the core fluid is much more rapid for the enhanced heat exchanger.

Fig. 3 Copper mesh enhancement factor for cryogenic crystal, porosity = 0.75.

4. FINITE ELEMENT ANALYSIS

To investigate the effect of the enhancement on heat transfer, a finite element analysis was performed. The above described crystal was analyzed for the APS Undulator A at a machine current of 50 mA at a distance of 30 m from the source. The total beam power was about 1800 W, and the peak power density at normal incidence was 75 W/mm². The crystal was inclined at 70.5° and set to diffract 4.2 keV photons from the (111) planes. The temperature profile for the enhanced crystal is shown in Fig. 4. The approach Reynolds number was 100,000, which corresponds to a total volumetric flow rate of 7.2 gpm. The inlet temperature of the liquid nitrogen was 78 K. The peak temperature on the crystal surface was 114 K. There is significant spreading of the heat in the crystal as indicated by the minimum crystal temperature of 81 K. The peak temperature for the unenhanced crystal was calculated to be 146 K.

5. CONCLUSIONS AND RECOMMENDATIONS

The cooling of high-heat-load synchrotron optics with liquid nitrogen is very promising. Because the primary resistance to heat flow for cryogenic crystals is at the fluid-solid interface, convection enhancement can provide significant thermal improvement. The calculations performed indicate that a porous-matrix-enhanced monochromator crystal should be able to handle the beam from APS Undulator A at 50 mA. An optimized crystal inclined at a larger

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STEP=1

ITER=5

TEMP

SMN =80.121

SMX =114.048

XV =1

YV =1

ZV =1

DIST=5.678

YF =-0.9925

PRECISE HIDDEN

A =82.669

B =86.365

C =90.062

D =93.758

E =97.454

F =101.151

G =104.847

H =108.543

I =112.239

Enhanced Cryo Crystal, Re=100k, APSUndA, 50mA, Si(111), A, 2k x V, D=30m, I=70.5A

Fig. 4 Surface Temperature Profile for Enhanced Cryogenic Crystal

angle (e.g., 80° - 85°) should push its range beyond the 100 mA goal. Additionally, the calculations were performed for the power load from all harmonics. Significant improvement will occur if only the central cone of the undulator beam is allowed to intercept the first crystal. The large thermal capacity of the enhanced crystal should allow it to perform well for a wiggler beam as well. An enhancement factor of 5 to 6 was calculated. This number corresponds well with the number measured for front-end components. Actually, the cryogenic mesh may perform better because of increased thermal conductivity of the silicon and copper.

The analytic model should be solved for a constant heat flux boundary condition and compared with data obtained for this type of matrix from experiments on the front-end components.⁹ These experiments were carried out with a constant heat flux.

At present, tests are underway to bond a copper porous matrix into a core-drilled silicon crystal and measure its rocking curve at liquid nitrogen temperatures to determine if a strain-free bond can be produced.

6. ACKNOWLEDGMENTS

The author wishes to thank Jeff Collins for discussions concerning porous media heat transfer enhancement. This work was supported by the US Department of Energy, BES-Materials Science under contract no. W-31-109-ENG-38.

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