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APPLICATIONS OF HEAT PIPES FOR HIGH THERMAL LOAD BEAM LINES

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ABSTRACT

The high flux beam produced by insertion devices often requires special heat removal techniques. For the optical elements used in such high thermal load beam lines, the required precision demands a highly accurate design. Heat pipe cooling of critical elements of the X-1 beam line at the National Synchrotron Light Source is described. This method reduces vibrations caused by water cooling systems and simplifies the design.

In some of these designs, deposited heat must be transferred through unbonded contact interfaces. A pinhole assembly and a beam position monitor designed for the X-1 beam line both transfer heat through such interfaces in an ultrahigh vacuum environment. The fundamental design objective is that of removing the heat with minimal interface thermal resistance.

We present our test method and results for measuring the thermal resistance across metallic interfaces as a function of contact pressure. The design of some devices which utilize both heat pipes and thermal contact interfaces will also be described.

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INTRODUCTION

The thermal problems associated with intense synchrotron radiation from wiggler/undulator sources impinging on sensitive beam line components require novel solutions. The power densities are comparable to these at the sun's surface.¹ Water cooling is widely used; however, optical and vacuum considerations sometimes constrain the design of cooling systems and require the use of other cooling mechanisms. Heat pipes, because of their simple structure, low cost, quiet mechanical behavior and ease of electrical isolation, are often the cooling system of choice.

This paper addresses several examples of the application of heat pipes for high thermal load beam lines at the NSLS. A pinhole system for the x-ray undulator beam line X-1 will use heat pipes as the principle means of removing heat in order to eliminate vibrations caused by water cooling. Other heat pipe systems have been used to cool beam position monitors and beam defining masks in order to electrically isolate these components. In some of these designs, where commercial heat pipes have been used as the main thermal conductors, heat must be removed through partly joined metallic interfaces in ultrahigh vacuum. We discuss our testing of both the heat pipes and the thermal interfaces.

HEAT PIPES

The typical heat pipe consists of a tube lined with a capillary structure and saturated with a volatile liquid. When heat is applied to one end of the pipe (the evaporator), the working fluid is vaporized and the heat travels to the other end (the condensor), where the heat is removed and the vapor condenses back into the capillary structure. The working fluid is replenished in the evaporator section by capillary action.

The principle behind the heat pipe was first described in 1942. In 1963 Los Alamos Scientific Laboratory began to investigate its use for space technological applications. Since then, heat pipes have been used in many applications, from cooling electronic circuits to heating automobiles.²⁻³

The theory of heat pipe operation was first developed by Cotter and Grove.⁴⁻⁵ In steady state operation, the radius of curvature of the meniscus at the liquid-vapor interface in the evaporator section (r_e) is more concave than that in the condensor section (r_c). Thus, the pressure gradient in the working fluid drives the fluid from the condenser to the evaporator⁶ via

$$\Delta P = P_e - P_c = 2\sigma \left(\frac{\cos \beta}{r_e} - \frac{\cos \gamma}{r_c} \right)$$

where σ is the surface tension, P is the pressure in the working fluid, r is the meniscus radius of curvature and β and γ are the wetting angles in the evaporator and condenser respectively. The driving pressure should be larger than the capillary structure pressure losses or

$$\Delta P > P_1 + P_2 + P_3$$

where P_1 is the viscous drag pressure loss, P_2 is the pressure loss due to the opposing vapor flow, and P_3 is the pressure head caused by gravity and depends on the heat pipe's orientation.

The maximum heat transfer rate may be expressed as⁶

$$Q = \frac{\sigma A D h}{b \nu L}$$

where σ is the surface tension of the working fluid, ν is the kinematic viscosity of the working fluid, b is a capillary constant (~ 16 for a cylindrical unobstructed capillary and ~ 20 for a wire mesh capillary), A is the free flow area in the wick, D is the hydraulic diameter of an individual capillary, L is the capillary length, and h is the latent heat of vaporization of the fluid.

The operating temperature of a heat pipe is dictated by its working fluid. In Fig. 1 typical fluids and their operating temperatures are given. For cooling beam line components, water may be used as the working fluid in the range from 25°C to 300°C ; OFHC copper is a good envelope and wick material as it is compatible with both water and UHV.

An important advantage of the heat pipe is its high heat transfer capacity per unit weight. A comparison of a heat pipe with a copper bar is shown in Table 1.

PINHOLE COOLING

For soft x-ray imaging experiments it is necessary to have a beam of sufficient spatial and temporal coherence. The spatially coherent part is selected by using a pinhole. The pinhole is a high power element because more than 150 watts of synchrotron radiation will impinge on the system from the X-1 undulator.⁸⁻⁹ Cooling is necessary to avoid thermal damage to the pinhole. The pinhole is the effective x-ray source of the system and any change of its position will move the image and change the monochromator's output wavelength. Ten micron repeatability of the pinhole's position is necessary and vibration of the pinhole must be avoided. The pinhole assembly will allow selection of any of five pinholes without breaking vacuum. These considerations all restrict the cooling system's design.

We have compared cooling by heat pipes and by laminar flow water cooling. The results have made it clear that heat pipe cooling will be able to remove more heat and will also be simpler to maintain.¹⁰ Figure 2 shows an assembly view of the pinhole system. The heat pipes are mounted from the top flange of a three axis manipulator. There are four 550 mm long, 4.76 mm diameter heat pipes. The working fluid is water and the envelope and wick material is oxygen free copper to cover the working temperature range from 25°C to 50°C. The heat pipes are designed to withstand a maximum temperature of 170°C without damage.

The individual pinholes are made by laser drilling (typically in platinum) and are clamped to two beryllium copper blocks. Each of the blocks are brazed using an indium alloy to two heat pipes which are connected to a natural convection heat sink on the cold end as shown in Fig. 3. Table 2 shows the design parameters.

Finite element analysis¹¹ has been used to calculate the temperature distribution of the pinholes and the clamping blocks. The thermal resistance chain and the temperature distribution system is shown in Fig. 4.

POSITION MONITOR AND MASK COOLING

A synchrotron radiation beam position monitor has been designed to withstand power densities up to 3000 W/cm². The cooling system using heat pipes, a water cooled heat sink, and a clamping structure to a tungsten photocathode is described in another paper of this conference.

Figure 5 illustrates the design of mask assembly using heat pipes as the principle means of removing heat. Because the mask is electrically isolated, it could also act as a beam position monitor to collect the photoemission signal. A two-axis device using four heat pipe cooled masks driven by stepping motor has been designed. The maximum total power to be absorbed here is only 20 watts, with 200 W/cm² maximum power density.

THERMAL TESTS

As described above, various clamping structures are used in the cooling system. In order to check our calculations, we have performed conductance measurements on the metallic interfaces in vacuum.¹² The results shown in Fig. 6 illustrate the thermal resistance as a function of contact pressure for copper, beryllium copper, as well as a combination of the two with platinum foils pressed between them. The resistance depends on the rms surface roughness (3000 Å for this experiment) and other material properties.

A test of the system for cooling pinholes has been done using an electron beam welder to simulate the power loading of the undulator beam. Fast time response thermocouples were used in these tests and an IBM PC microcomputer, equipped with a multichannel temperature data acquisition system, was used to acquire the data. Figure 7 shows the temperature of the pinhole and clamping block being illuminated with 30 watts total power (maximum power density of 950 W/cm²). No damage was observed on the 30 µm pinhole after more than 30 minutes exposure to the heat source. No vibration was observed on the free end of the heat pipe assembly.

SUMMARY

As a cooling method for high thermal load beam lines, heat pipes eliminate vibrations caused by water cooling and simplify mechanical design. Cooling systems for pinholes, monitors, and masks using commercial heat pipes and metallic clamping structures have been designed. It should also be possible to develop heat pipe cooling of other optical elements such as mirrors and crystals.

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FIGURE CAPTIONS

- Fig. 1. Typical fluids for heat pipes and their operating temperatures (from Hughes Aircraft Company, Electron Dynamics Division, Torrance, CA).
- Fig. 2. NSLS X-1 pinhole system.
- Fig. 3. Heat pipes and clamping structure for cooling X-1 pinholes.
- Fig. 4. X-1 pinhole system temperature distribution.
- Fig. 5. Mask assembly which also can act as a beam position monitor, using heat pipes for cooling.
- Fig. 6. Temperature difference across clamping interface as a function of contact pressure.
- Fig. 7. Temperature rise of the pinhole (top curve) and clamping block (bottom) being illuminated with 30 watts at a distance of 7 mm far from the pinhole center.
- Fig. 8. Test assembly of the heat pipe cooling system.

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Fig. 1

Fig. 2

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Fig. 3

- R1 Heat sink
- R2 Interface of heat sink and heat pipe
- R3 Heat pipe
- R4 Thermal buffer block
- R5 Clamping structure interface
- R6 Pinhole disk

Fig. 4

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Fig. 5

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Fig. 6

PIN HOLE INTERFACE TEST

30 w Electron Beam

Fig. 7

Fig. 8

Comparison of a typical heat pipe with solid copper bar

		Heat pipe	Copper bar
Transport power	(W)	200	200
Length	(mm)	610	610
Diameter	(mm)	12.7	76.2
Temperature differential	(°C)	0.5	70
Weight	(kg)	0.34	24

Table 2

Design parameters of the X-1 pinhole cooling system

Maximum incident power density	(W/cm ²)	400
Maximum incident total power	(W)	120 (mask) 30 (pinhole)
Number of pinholes		5
Pinhole diameters	(μm)	25 - 500
Adjustment range horizontal	(mm)	25
vertical	(mm)	150
Adjustment resolution	(μm)	2.5
repeatability	(μm)	5
Driver		Stepping motor or manual
Vacuum	(torr)	10 ⁻⁹

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