A DISCUSSION ON UTILIZATION OF HEAT PIPE AND VAPOUR CHAMBER TECHNOLOGY AS A PRIMARY DEVICE FOR HEAT EXTRACTION FROM PHOTON ABSORBER SURFACES

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Abstract

Heat pipes and vapour chambers work on heat exchange phenomena of two-phase flow and are widely used for industrial and commercial applications. These devices offer very high effective thermal conductivities (5,000-200,000 W/m/K) and are adaptable to various sizes, shapes, and orientations. Although they have been found to be an excellent thermal management solution for laptops, satellites, and many things in-between, heat pipes and vapour chambers have yet to be adopted for use at particle accelerator facilities where they offer the possibility of more compact and more efficient means to remove heat from unwanted synchrotron radiation. As with all technologies, there are inherent limitations. Foremost, they are limited by practicality to serve as local heat transfer devices; heat transfer over long distances is likely best provided by other means. Heat pipes also introduce unique failure modes which must be considered.

INTRODUCTION

The heat pipe or, more-generally, a vapour chamber, is a device used to facilitate rapid heat transfer via phase-change. The process requires only a moderate temperature gradient and requires no additional power input. Typically, the heat pipe is used to move energy short distances from heat sources to heat sinks. [1,2] Because of the large transfer of heat associated with a phase change and rapid fluid flow that generally develops in these devices, heat exchange can be well beyond the limits seen in simple conduction or convection-based approaches. The operating principle is simple: A fluid in its liquid state enters the evaporative section of the pipe where it is heated, causing it to evaporate. The vapour then travels to the condensation section where it is liquefied and releases the heat it absorbed in the evaporative section.

Present designs for the APS Upgrade call for photon absorbers which are cooled strictly by convective water flow, as it has conventionally been done. However, consideration of the thermal stresses that will result from intercepting the concentrated beams of synchrotron radiation that are expected with the upgrade suggests that absorber design options, particularly material and geometry choices, will be severely limited. Particularly it is critical as there is a little space afforded by the new, higher-performing MBA lattices that are being evaluated. Another issue of concern is vibration. For required beam performance, exceptionally low levels of vibration are needed to ensure that the particle beam can be precisely steered though lattice magnets. Heat pipes would likely help to reduce vibration as they would reduce the amount of cooling water flow needed to maintain absorber surface temperatures to an acceptable level.

Presently, alternatives like heat pipes are being explored for manufacturing feasibility, economic operation, and ease of fabrication. To help answer these questions, analysis of a conceptual absorber utilizing heat pipes was performed. MATLAB was used to calculate heat pipe performance characteristics based on geometry and other factors and ANSYS was used to perform finite element thermal simulations. The results show that heat pipes can meaningfully improve thermal performance. There are, however, lingering concerns about the reliability of heat pipes for *accelerator applications* which cannot be addressed with such analysis.

Heat Pipe Limiting Factors

A number of design options should be considered when choosing to implement a heat pipe. One such option is the *chamber design*. Thin walls and conductive materials may help to enhance thermal transfer but such choices also may mean that the heat pipe is less mechanically robust. Another option is the *fluid type*. Fluids should be selected which optimize the heat transfer process but which also should not cause corrosion or other degradation of the wick and chamber materials. A number of experiments have established a commonly used list of compatible metal and fluid combinations. [3] There is considerable flexibility in the *wick design* as well. Wicks may consist of a mesh that liquids are squeezed through, they may consist of fibers that guide liquid along, or they may even consist simply of grooves built into the heat pipe wall. Each option offers a different set of advantages and disadvantages which should be weighed relative to the needs of the specific application.

There are a number of physical limitations which impact the transport capabilities in a heat pipe. These include: *capillary pressure difference* - which must exceed the limits introduced by the fluid flow in order to properly move and sustain the motion of the liquid and vapour [1]; *sonic limitations*, or *bottlenecking of fluid* at state change regions, which must be avoided [2]; *entrainment*, or the tendency for droplets of liquid to get caught up in the vapour flow can disrupt flow [2]; *boiling and bubble formation* in the liquid filled wick can also limit the heat capacity [1]. Many of these phenomena will be the result of excess heat capacity. Which limiting factor will limit

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the performance of a heat pipe at a given temperature and that will depend on the heat pipe design. Often, graph as shown in Fig. 1 can be plotted for any given heat pipe to visualize the trends of the limitations. (MatLab program developed based on theory presented in [4-11]).
Moreover, there is a chemical compatibility issue with presence photon radiation and interaction with operating fluid, construction material at an operating temperature, [3] which is not discussed here.

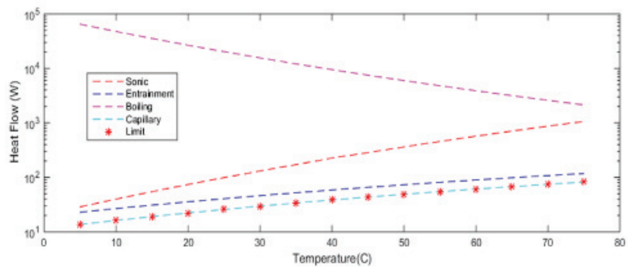

Figure 1: Example of a heat pipe limitations graph for approximately 6 mm diameter heat pipe containing water as working fluid.

FINITE ELEMENT ANALYSIS

In regards to the application, the simulated absorber has a V-shaped surface to intercept unwanted radiation and a rectangular hole to allow passage of useful radiation. Any heat pipe assembly would be used to move heat developed in the body of the absorber to a water-cooled heat sink. Fig. 2 shows the conceptual absorber geometry, computed power profile, and results from an ANSYS thermal simulation.

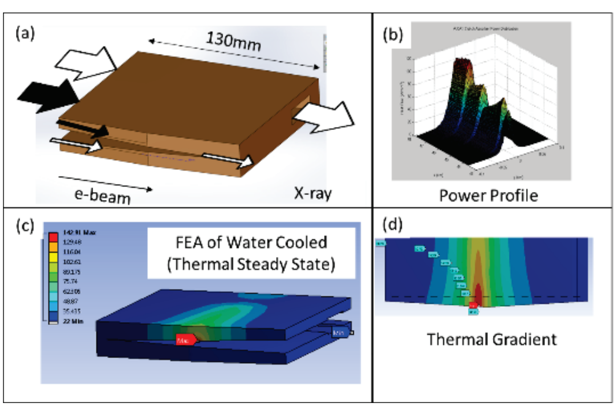

Figure 2: (a) conceptual absorber design for the APS-U (b) computed power profile, (c) FEA result, and (d) thermal gradient.

The four theoretical models were employed to assess performance improvement due to the heat pipe. In order to set establish conductivity values, custom materials were created and assigned to different parts of the assembly for each model.

(1) Pipe is modelled as a hyper conductive rod allowing identify other resistances to be quantified and an equivalent thermal conductivity for the heat pipe to be established.
(2) Multiple layers of the heat pipe are modelled using rule of thumb conductivity values to understand "worst case scenarios."
(3) Variations on the hyper-conductive rod and multiple layer model simulations are performed which treat temperature as a constant 2-5°C difference and alter the conductivities to achieve this.
(4) Treat the heat pipe's temperature difference as a few degrees constant. Set the contact thermal conductance to rule of thumb values and change the thermal conductivity of the heat pipe to achieve desired temperature change.

Generally, it was found that, regardless of the method used, a heat pipe reduces the temperature gradient on the absorber surface (Fig. 3). Some of the worst-cases scenarios showed only a marginal improvement in performance relative to the baseline design while others indicated a larger benefit is achievable, but all cases suggested that the heat pipe is a reasonable option in this application.

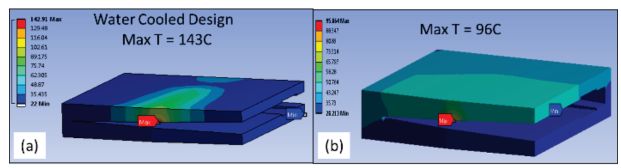

Figure 3: Comparison between water cooled design and heat pipe design.

Modelling Method Variation

In regards to the variations examined in each method, it is clear that the greatest focus on improving the system's thermal performance is creating large heat sink surface area around the high heat flux regions. This can be done via methods like increasing diameter and creating a greater density of heat pipes towards it. While other factors like the number of heat pipes and length are important, the effects can be small in comparison. It is also important to look at the design of the heat pipe itself, as the temperature performance is highly dependent on the thickness of the layers of wall, wick, and vapour.

RELIABILITY ISSUES

Start-up Conditions

Over time, of course, a heat pipe will gravitate towards a stable operating thermal gradient. However, during start up the temperature gradient may vary considerably. Conditions in the heat pipe leading to these variations include uniform distributions of the fluid, frontal distributions associated with a loss of the uniformity as the fluid reaches the condenser, and frontal distributions which lack condensable gases resulting in a sudden drop off in temperature. Initial temperature and the rate of start-up can be large factors in the development of such conditions. [7]

Failure is a legitimate concern under such conditions. Possibilities include: capillary pumping failure, boiling, dry-out from a frozen fluids restricting the self-replenishing nature, and entrainment of the liquid flow. In addition, low thermal resistance at the condenser can overwhelm the system and enhance the probability that such failures will occur. There are ways to avoid some of these failure modes, for example utilizing an entrainment limit which exceeds sonic limit. However, solutions to such problems, and the degree to which they may be avoided are strongly dependent on the specific application.

Structural Stability

It is important to note that heat pipes may be required to withstand vibrations, shock, and severe temperatures. Copper and, to a greater extent, GlidCop™, may be used to construct a heat pipe with very thin walls owing to the strengths of those materials. The minimum thickness may be found using equation given below and it is assumed to be effective at the same bonding temperature as assumed in the base problem. [1]

$$t=(P\cdot r)/\sigma_r$$

In this case, σ_r is a tenth of the wall's ultimate tensile strength, P is the vapour pressure at the temperature, and r is the internal radius of the pipe walls.

Material Compatibility for Operation

One major aspect of designing the heat pipe system is material compatibility. Some fluid and solid combinations will result in chemical reactions that develop gas pockets which hamper or cease operation of the heat pipe [3]. Water is known to be generally compatible with copper however compatibility between water and GlidCop™- another common absorber material, is less established. The Acetone or some refrigerants would be some potential alternatives by being compatible with both [1]. However, these would offer notable downgrades in performance capabilities.

Contact Variance

Another major concern is the thermal interaction between the heat pipe and the absorber.

Manufacturing Concerns

Manufacturing heat pipes requires the development of a shell, the insertion of a wick, and filling the pipe with fluid as it is sealed off at one of the ends. Afterwards, some experimentation is need on any given heat pipe to ensure it performs as intended. At the same time, to achieve the design needed, the evaporative section needs to be built into the absorber itself for all the heat pipes. This also solves the question of how to connect the heat pipes to the absorber. The issue that arises with this is, considering the reliability of manufacturing one heat pipe is in doubt enough to call for basic tests on all of them, would see an assembly with dozens of heat pipes become a potential manufacturing difficulties to a considerable degree.

The precise precision of manufacturing methods can also generate heat pipe with different pressure in each product and it does offer enough to concerns to clarify and gauge how extensive potential complexities that arise from manufacturing process.

CONCLUSION

Heat pipes offer an attractive solution for efficient and compact transport of heat in photon absorber applications. Simulations show that heat pipes offer tangible improvements over conventional water cooling. However, a number of potential disadvantages should be weighed against the performance improvements. These include potentially more complex and costly fabrication, limited performance predictability, and reliability. Continued investigation is warranted, particularly as the requirements for next generation accelerators continue to become more challenging.

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