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LANCASTER, PENNSYLVANIA

ACTIVE TWO PHASE COOLING OF OPTICS

FINAL TECHNICAL REPORT

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EXECUTIVE SUMMARY

Two phase cooling of a higher powered laser optics offers a significant potential to advance the state-of-the-art in laser mirror cooling. Significant improvements can be achieved through the transfer of heat via working fluid phase change rather than specific heat capacity. These benefits include reduced jitter, and reduced electrical power consumption.

In one actively pumped two phase cooling scheme, a saturated liquid is mechanically pumped into a porous metal layer under the mirror face where a fraction of the fluid is vaporized. The vapor-liquid mixture then leaves the face area and flows to a condenser. The condensate recirculates back to the mirror in a closed loop process. Because the working fluids have high latent heats of vaporization compared to their liquid heat capacities, a significant reduction in flow rate and pressure drop is possible.

Analytical and experimental work has shown that a favorable combination of low distortion and low jitter is achievable with this approach. Also, since two phase heat transfer coefficients increase with increasing heat flux, a two phase cooled optic will achieve a lower distortion under non-uniform beam profiles.

Jitter data were collected at absorbed heat fluxes up to 80 W/cm^2 using a molybdenum demonstration mirror with methylamine coolant at 20°C . Low distortion coefficients were used as a design goal for this program at an absorbed heat flux up to 100 W/cm^2 . A demonstration mirror was fabricated and tested for thermal/optical performance at the Thermal Distortion Test Facility (TDTF) located at the Kirtland AFB, New Mexico. Thermal performance levels in excess of 100 W/cm^2 were demonstrated. Tests conducted at the TDTF showed thermal distortion coefficients at or below the design goal for absorbed heat fluxes up to levels in excess of 100 W/cm^2 . No other cooling approach has been demonstrated that uses a low flow rate, low pressure drop cooling scheme, and demonstrates low jitter and low thermal distortion at absorbed heat fluxes near 100 W/cm^2 .

Further development of this promising technology is recommended. Follow-on work should include automation and instrumentation of the cooling support loop, hardware scale-up of cooled optics in low thermal expansion materials such as silicon and silicon carbide, improved fundamental modeling of the pumped two-phase cooling process, and improved filtering and leak detection equipment.

INTRODUCTION

Several of the directed-energy defensive weapons systems under evaluation by the Strategic Defense Initiative Organization (SDIO) include advanced high-power optics as a primary component. These mirrors are required to remain optically flat while absorbing heat fluxes in excess of 100 W/cm^2 . These mirrors may reach diameters of over one meter and operate in space or in a terrestrial environment. Current conventional cooled mirror designs use single phase, liquid-cooled channels located beneath the optical surface. Liquid coolant is circulated through these channels, and the mirror's absorbed heat is removed by heating of the liquid.

Conventional single-phase cooling methods have unfavorable qualities that adversely affect mirror performance. The coolant temperature increases as the fluid flows across the mirror because the cooling mechanism uses the liquid heat capacity. To minimize the effect of this temperature increase on the thermally induced distortion of the mirror, relatively large coolant flow rates are required. To minimize the wall-to-fluid temperature drop, the fluid velocity is increased by using many small flow channels under the mirror face. Large pressure drops are thus developed in these mirrors.

High flow rates and pressure drops in conventional mirror designs result in the need for large pumps. These pumps impose large power requirements on optical systems and can be a considerable source of mirror jitter due to pump induced flow disturbances. A large silicon mirror using this conventional cooling may necessitate a pump power requirement up to 1 mWe. This large electrical power requirement certainly diminishes the attractiveness of single-phase cooling technology.

Active two-phase cooling offers an attractive alternative. In a two phase cooled mirror, a liquid is injected onto the back of the optical face where the absorbed heat causes a portion of this fluid to be vaporized. The generated vapor then flows away from the optical region to a condenser, where the vapor is condensed, and the condensate is collected for recirculation. Cooling the optical face in this fashion has the potential to significantly reduce mirror coolant flow rate, pump power requirements, mirror jitter and distortion.

For the past seven years, Thermacore has been involved in the development of both passive and active two-phase cooling technology for laser mirrors. This work has proceeded through several programs. In a program administered by the Materials Laboratory at Wright Patterson Air Force Base (Contract F33615-85-C-5017), a single-element actively pumped two-phase cooled silicon mirror was designed, built and tested for thermal and optical performance at the Thermal Distortion Test Facility (TDTF) at Kirtland Air Force Base, New Mexico. Absorbed heat fluxes in excess of 140 W/cm^2 were demonstrated during tests, but an off-center anomaly in the optic resulted in higher distortion levels than predicted by theory.

Since this earlier work, emphasis has been directed to the development of a multi-element active two-phase cooling scheme which demonstrates both low jitter and low distortion, while removing absorbed heat fluxes in excess of 100 W/cm^2 . In a program monitored by Los Alamos National Laboratory (Subcontract 9-X28-1472-G), a series of investigations were performed to evaluate the integration of pumped two-phase cooling into large-diameter optics. Favorable results were obtained in these investigations. In addition to analytical work, experimental work was performed to define a simple and low-cost method of implementing the cooling scheme, and to demonstrate the technology by experimentally verifying low jitter and distortion in subscale cooled optics at the required heat flux. The purpose of this Final Report is to present the results of the recent work.

PROCESS DESCRIPTION

The differences between single-phase and two-phase mirrors are a direct result of the fundamental differences in the approach to cooling the mirror face. Whereas single-phase cooling uses the specific heat of a liquid to remove absorbed heat from the mirror face, a two-phase cooling scheme uses the latent heat of vaporization of the working fluid. Since boiling proceeds isothermally in the absence of a large pressure gradient, two-phase cooled mirror surfaces can be maintained at a more uniform temperature than single-phase cooled mirror surfaces. A second major advantage of two-phase cooled mirrors results from the lower flow rates required by two-phase cooling. Since flow rates and pressure drops are small, significant reductions in pumping power and mirror jitter are achievable.

A conceptual drawing of the mirror is shown in Figure 1. Saturated liquid enters the inlet ports and is injected into a sintered powder metal wick structure beneath the mirror face. The fluid flows radially to discharge passages adjacent to the injection ports. A strong back provides support for the mirror face. A fraction of the fluid in the wick changes phase from liquid to vapor. The two-phase mixture leaving the face region is then collected and returned to a liquid in a condenser located behind the mirror assembly. The condensate is then recirculated back to the mirror face.

REDUCTION TO PRACTICE

Methods were developed to integrate two-phase cooling technology into large-diameter optics to meet SDIO requirements. These two cooling schemes have been named the Thin Wick Concept and the Radial Flow Concept. Both arrangements use a thin powder metal wick structure beneath the mirror face to carry the vaporizing coolant. The Thin Wick Concept uses parallel streamline flow, whereas the Radial Flow Concept utilizes radial flow from equally spaced injection points. Both concepts showed promise for further development since they included a fluid distribution scheme that can be scaled to a large diameter with a minimal effect on the overall mirror pressure drop. Maintaining a low pressure drop is important for minimizing optical distortion and pump power requirements.

Pumped Two Phase cooling features a combination of low coolant flow rate, low pressure drop, and near-isothermal coolant temperature

Figure 1. Active Two-Phase Cooled Optic Heat Exchanger Concept

Theoretical and experimental work was performed by Thermacore and United Technologies Research Center (UTOS) to establish which concept provides the best cooling and ease of fabrication. Work was also performed to establish a density of injection and removal points for each concept to, provide acceptable performance while also minimizing fabrication costs. The main parameters affecting the performance of the cooling scheme were determined to include injection point spacing, wick type and particle size, wick thickness, choice of coolant, and coolant flow rate.

FUNDAMENTAL STUDIES

To model two-phase heat transfer in the wick, an extended surface model was developed to predict the performance of heat-transfer surfaces covered by porous structures. A relationship was demonstrated between nucleate boiling from plain and porous surfaces, and an equation for surface enhancement factor was presented. Good agreement with data was obtained for several cases of interest, including sintered metal powder heat pipe wicks, pool boiling from sintered powder and sintered fiber covered surfaces, and pumped two-phase cooling in porous media. A closed form analytical model was presented for thick porous structures, and a numerical approach was developed for thin porous structures. For nucleate boiling heat transfer from porous surfaces, the analytical model provides a straightforward method of performance estimation that is useful for design purposes. This approach was then applied to the design of cooled mirrors. Methylamine was selected as the coolant because of its good heat transport properties, moderate vapor pressure, and compatibility with the materials of construction. A

tungsten porous wick was selected for the wick material because of its high thermal conductivity, low thermal expansion coefficient, and relative ductility as compared to frit-bonded silicon powder wicks.

Experimental data were collected using methylamine injected into a -120+140 sintered tungsten wick with closely-spaced radial flow geometry. Saturated liquid methylamine at 20°C was injected into a 635 μ m thick tungsten wick and forced to flow through the wick to discharge ports. The flow was maintained at a rate sufficient to keep the wick entirely wetted. Thus, a pump-augmented cooling approach does not have to depend on capillary or gravity forces to maintain a flooded wick. The exit quality was generally less than 100%. Figure 2 shows data collected using this approach in comparison with the extended surface model.

The upper and lower theoretical curves are based on a model using measured wick thermal conductivity and thickness as a lower bound, and using modified properties. The upper bound prediction accounts for tortuosity of the heat conduction path in the wick. The model is in excellent agreement with the data over nearly two orders of magnitude of heat flux. The prediction using measured wick properties provides a closer prediction to the data than the prediction based on apparent wick properties. The onset of dryout is accompanied by a shift of the data to the right.

Figure 2. Heat Transfer Data for Mechanically-Pumped Two-Phase Cooling in Porous Wick

Data were also collected using a similar wick structure, but with a Thin Wick cooling flow scheme. The results of these tests were not as favorable as the Radial Flow data. This result is believed to be due to increased tendency of vapor to build up in heated areas of the mirror wick with the Thin Wick design.

THERMAL DISTORTION PREDICTIONS

Using the nucleate boiling heat transfer model, a detailed thermal profile was produced for three inch diameter active two-phase cooled mirror designs. This was done for both a Thin Wick design and a Radial Flow design. Based on parts drawings and predicted thermal profiles supplied by Thermacore, UTOS completed a thermal distortion profile calculation for each design. The calculation assumed methylamine coolant and a flat beam profile with 100 W/cm^2 absorbed heat flux. Although the analysis predicted that both designs were capable of meeting the design goal, the Radial Flow design was superior with respect to predicted distortion and experimental performance tests. It was therefore selected for fabrication and technology demonstration tests.

TECHNOLOGY DEMONSTRATION

The technology was developed to fabricate three inch diameter Radial Flow demonstration mirrors. An exploded view of the mirror assembly is shown in Figure 3. A tungsten wick structure serves dual functions of an extended heat transfer surface and a method of bonding the mirror faceplate to the artery plate. Molybdenum was selected for the technology demonstration

Figure 3. Radial Flow Design Exploded View

mirrors because of low cost, ease of fabrication, and close thermal expansion match to the tungsten wick. Interferometry was performed at up to 50 psig of internal pressure, which demonstrated that the wick was uniformly well-bonded to itself as well as to the artery plate and faceplate.

THERMAL PERFORMANCE TESTS

Thermacore performed thermal performance tests on a three inch diameter demonstration mirror. An absorptive coating was applied to the mirror face, and a xenon arc lamp was used to radiatively heat the mirror face.

Thermal performance testing was performed at heat fluxes up to 90 W/cm^2 . A thermocouple was epoxied into a groove cut into the surface of the mirror face. The thermocouple was located in the center of an illuminated 0.75 inch diameter region. Data taken at an absorbed 90 W/cm^2 heat flux showed that the temperature difference between the center face temperature and the coolant temperature was nearly 27°C . The predicted temperature difference between the center of the heated external surface and the coolant is nearly 27°C , i.e., very close to the measured temperature difference. This result indicated that the optic was performing as designed.

JITTER TEST RESULTS

Jitter testing of a three inch diameter active two-phase cooled molybdenum mirror was completed during November, 1989 at UTOS in West Palm Beach, Florida. Jitter testing was completed at heat fluxes up to 80 W/cm^2 . A xenon arc lamp was again used as the heat source for these tests.

Low jitter levels were demonstrated by experiment. Table i shows a summary of the jitter test results. It was determined from tests that the jitter forces from a two-phase cooled optic tended to increase slightly with increasing heat flux. Further tests are recommended to determine if slugging of the two-phase fluid in the exit channels or if vapor bubble generation in the wick is the cause of this effect. A comprehensive discussion of the jitter test results is presented in Technical Paper No. 2 and in Quarterly Progress Report No. 9. A normalized jitter/distortion parameter was defined to allow an objective comparison between cooling concepts. The previously calculated distortion coefficients were used to make the comparison. Active two-phase cooling demonstrates favorable low jitter and distortion, as compared with other HEL cooled mirror approaches.

DISTORTION TESTING

Distortion tests were performed on a three inch diameter molybdenum active two-phase cooled test mirror at the Thermal Distortion Test Facility, Phillips Laboratory, New Mexico. Tests demonstrated that favorable low distortion occurred for the optic using methylamine refrigerant operating near 20°C. A comprehensive Confidential Distortion Test Report dated September 16, 1991, (Interim Report) has been completed and delivered to LANL and Phillip Laboratory personnel. (See Report List)

Preheating of the refrigerant was used to prevent single-phase cooling and associated higher distortion levels. It was shown by experiment that favorable two-phase cooling occurred whenever the coolant inlet temperature and flow rate were such that at least 2% by mass of the coolant was vaporized in the wick. Both the total distortion coefficient (i.e., total growth divided by absorbed heat flux) and thermal ripple distortion coefficient (localized peak-to-peak growth divided by absorbed heat flux) were shown to decrease with increasing heat flux. This behavior is a useful result of the two-phase cooling, and it can be used in large cooled optics to produce a higher quality reflected beam pattern for non-uniform beam profiles. Figure 4 shows the variation in thermal ripple distortion coefficient with absorbed heat flux.

Figure 4. Measured Ripple Distortion Coefficient vs. Absorbed Heat Flux for Pumped Phase Change Cooled Optic

SUMMARY OF ACCOMPLISHMENTS FOR PHASE II SBIR PROGRAM ENTITLED, ACTIVE TWO PHASE COOLING OF OPTICS

- 1) Low distortion was proven by TDTF tests.
- 2) TDTF data results verified overall understanding of fundamental heat transfer mechanisms and have revealed areas for required modeling improvement.
- 3) The distortion prediction techniques developed by Thermacore and UTOS have been validated.
- 4) Thermacore has demonstrated the manufacturing technology for high-strength porous wick structures.
- 5) Thermacore has demonstrated a viable Radial Flow cooling concept that meets the performance requirements of space-based laser systems.
- 6) The program has verified a critical cooling technology for use in advanced low flow and low pressure optics.
- 7) Low jitter was demonstrated by testing performed at UTOS by Thermacore and UTOS.

TECHNICAL PAPERS PUBLISHED

1. J.H. Rosenfeld, *Nucleate Boiling Heat Transfer in Porous Wick Structures, Heat Transfer Equipment Fundamentals, Design Applications, and Operating Problems*, HTD-Vol. 108, ASME Book No. H00500-1989. (*unclassified*)
2. J.H. Rosenfeld, M.E. Meadows, and P.C. LaDelfe, *Advances in Pumped Phase Change Mirror Cooling*, Proceedings of 4th High Power Laser Optical Components Topical Meeting, Boulder, Colorado, October 22-23, 1990. (*unclassified*)
3. J.H. Rosenfeld, W.G. Anderson, R.F. Keller, M.E. Meadows, J.L. Stapp and P.C. LaDelfe, *Distortion Test Results from a Pumped Phase Change Cooled Mirror*, Proceedings of the 5th High Power Laser Optical Components Topical Meeting, Boulder, Colorado, October 21-22, 1991, submitted. (*Confidential*)

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