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Thin-Film Evaporative Cooling of a Side-Pumped Solid-State Laser Diode Oscillator for Space-Based LIDAR Applications

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Abstract

A concept for cooling side-pumped laser crystals, using a thin film of evaporating fluid, was investigated for use on future space-based light detection and ranging (LIDAR) instruments. Analyses of the solid crystal domain show that the thin-film cooling scheme will result in improved thermal management of the lanthanide crystal material investigated. Several candidate flow configurations are presented to produce the desired fluid flow across the crystal surface. One-dimensional, axial flow, two-fluid evaporation models were then solved to characterize the fluid and thermal performance of two of the proposed flow configurations. In addition, an incipience model is presented to determine the film thickness constraints necessary to suppress nucleate boiling. The bulk flow model indicates that excellent thermal management of the crystal, low liquid velocities, and low liquid pressure drops are possible with the two axial flow configurations analyzed. The incipience model indicates that liquid film thickness less than 10 microns may be necessary to ensure the complete absence of vapor bubbles in the liquid flowfield. This result indicates a need to develop three-dimensional fluid models for future studies so that more complex flow geometries may be studied.

Keywords: LIDAR, cooling, thermal management, thin-film, evaporative, NASA, solid-state, lanthanide, luminescent, crystal.

1. Introduction

NASA Langley Research Center has been actively developing a series of side-pumped, 2-micron output lasers as part of a long-term LIDAR risk-reduction program. A typical arrangement of the pump diodes and luminescent oscillator crystal are shown in Figure 1.

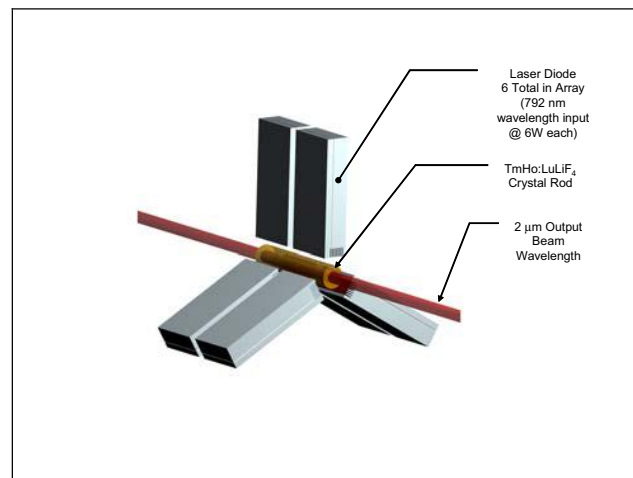


Figure 1

Side-Pumped Laser Crystal Oscillator Rod

The current LIDAR concepts at NASA rely upon conductive cooling as the baseline design for the thermal management of the side-pumped flight instruments. While totally passive, conductively-cooled configurations result in non-uniform temperature distributions across the crystal cross section, result in higher than desired crystal operating temperatures, and are sensitive to minor variations in contact pressure at the conductive interface. Improvements in laser output energy are gained with lower operating temperatures [10].

To promote improved cooling, provide nearly uniform exterior crystal temperature, and to allow lower operating temperatures, a concept for cooling the crystal by means of a thin evaporating liquid film flowing across the crystal surface was proposed and investigated. Several candidate flow morphologies were analyzed using a steady state, one-dimensional, two-fluid flow model. Analyses using this model were conducted using the properties of R507A and R508B azeotropic refrigerant fluids. Preliminary analyses of critical film thicknesses required to suppress nucleate boiling were performed using these same fluids. The combined results of the analyses indicate that temperatures below 223K (-50°C) are possible at the crystal surface, core temperatures below 237K (-36C), and concentric isotherms may be attainable. The results also indicate that liquid film thicknesses on the order of 10 microns may be necessary to ensure the complete suppression of nucleate boiling. More rigorous modeling and analysis are needed, and guidance for subsequent research is presented.

Methodology

In order to assess the merits of the thin-film cooling concept, first-order comparisons with conductively cooled thermal management schemes were found to be helpful. Starting with an assessment of desired cooling system metrics, the benefits and limitations of the two competing cooling technologies are then compared. The study then proceeded to define several candidate evaporative cooling configurations, to determine their operative limitations, and to provide guidance for the integration of this design with side-pumped LIDAR crystals in-situ. In particular, the methodology proceeded as follows:

1. Assessment of solid-state laser crystal thermal management requirements.
2. Temperature distribution through an ideal conductively-cooled crystal rod.
3. Temperature distribution through an ideal thin-film evaporative rod.
4. Description of thin-film evaporative candidate flow geometries.
5. One-dimensional hydrodynamic study of two axial-flow configurations.
6. Film thickness requirements to suppress nucleate boiling.
7. Sealing technology development.
8. Interfacial characteristics of the lanthanide crystal.

It can be seen from the list of topical areas that the design of such a system must be integrated into the overall package design of the LIDAR system. The investigative approach to the thermal management subsystem was conducted while the potential impacts on the structural, volumetric and power resources of the instrument package and satellite system being considered at every step. Such a system approach is considered to be crucial if the development of a new flight instrument technology is to be successfully integrated into a space-borne instrument. Although concepts and principles for sealing technology and interfacial performance are necessary to design a working prototype, the thermal and hydrodynamic performance between the solid crystal and the fluid film were addressed first. Therefore, only the thermal, hydrodynamic and incipience model results are presented here.

Solid-state laser crystal thermal management goals

Due to the low optical efficiencies of luminescent crystals, most of the incident energy is converted into heat. The quality of the luminescent crystal output is typically characterized by the pulse energy, and the central tendency around a single output wavelength. The pulse energy is increased with lower average crystal temperatures [10]. The output wavelength is affected by temperature as well. Consequently, large temperature gradients across the crystal, normal to the rod cross-section, produce a wider variance in the output wavelength. Consequently, any crystal thermal management system has three goals:

1. Prevent thermally-induced damage due thermally-induced stresses.
2. Maintain the average crystal at as low a temperature as possible.
3. Minimize temperature variation across the crystal.

To produce an unbiased comparison between the two competing cooling technologies, the cooled boundary is assumed to be a constant 223K for both concepts. This ignores any temperature limitation of current conductively-cooled prototypes. Performance differences are therefore determined solely by the difference in the geometry of the thermal boundary condition. Three performance metrics were computed for each case, maximum temperature, T_{\max} , average temperature, \bar{T} , and standard deviation, σ_T , across the 2-dimensional crystal domain. The crystal geometry analyzed is a 4mm diameter x 20mm long TmHo:LuLiF₄ rod. A volumetric heating of 36W was assumed. The thermal diffusivity of the crystal is such that the heating can be considered constant, therefore the intermittent effect of pulses was ignored. All analyses assume steady-state thermal operation.

Comparison of Temperature Distributions for Conductively-Cooled versus Evaporative-Cooled Crystal Rods

The cross-section of a conductively-cooled crystal is shown in figure 2. A three-node conductively-cooled configuration was used in the analysis.

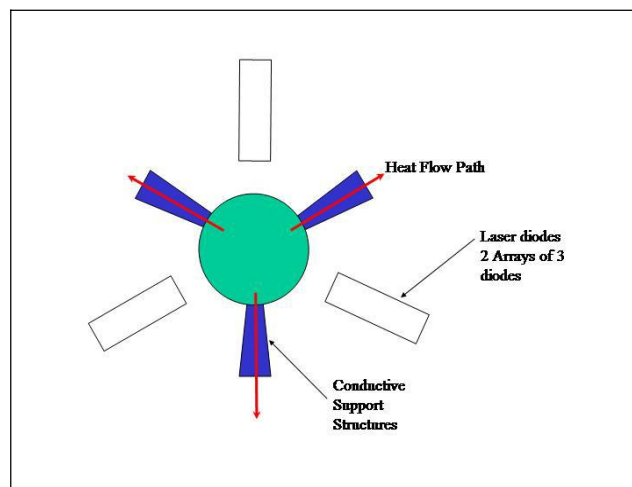


Figure 2

Cross-Section of a Conductively-Cooled, Side-Pumped Crystal Rod

The temperature distribution across the ideal conductively-cooled crystal is shown in figure 3. Note the obvious non-uniformity of the temperature gradients, indicative of the limited, discrete regions available for heat extraction.

In contrast, the temperature distribution of the evaporative-cooled geometry is shown in Figure 4. Note the concentric isotherms produced by the uniform temperature boundary condition. In addition to lower core temperatures, improvements in average temperature and temperature variation are indicated for the evaporative-cooled system.

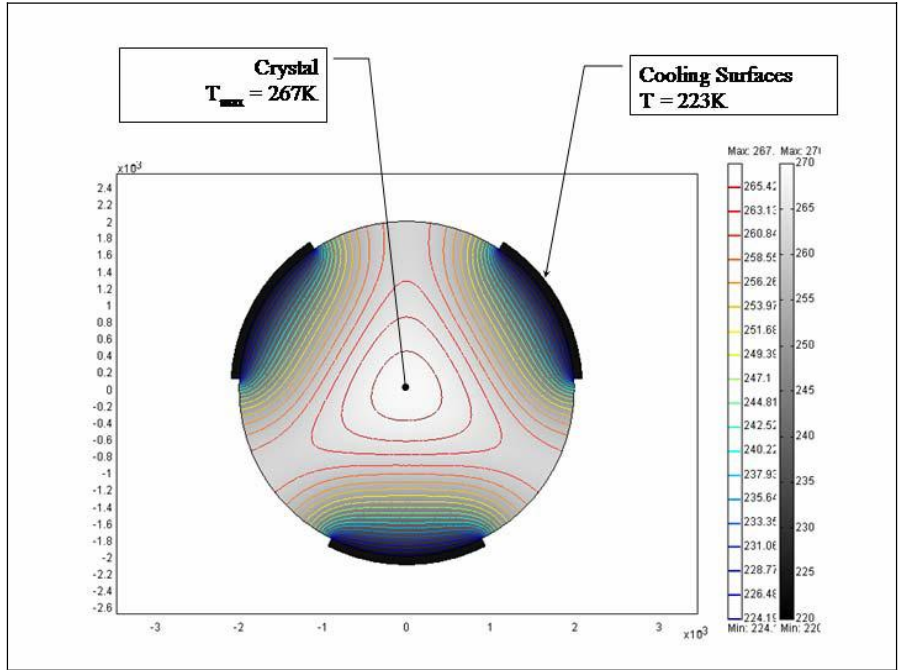


Figure 3

Temperature Distribution: Ideal Conductively-Cooled Crystal

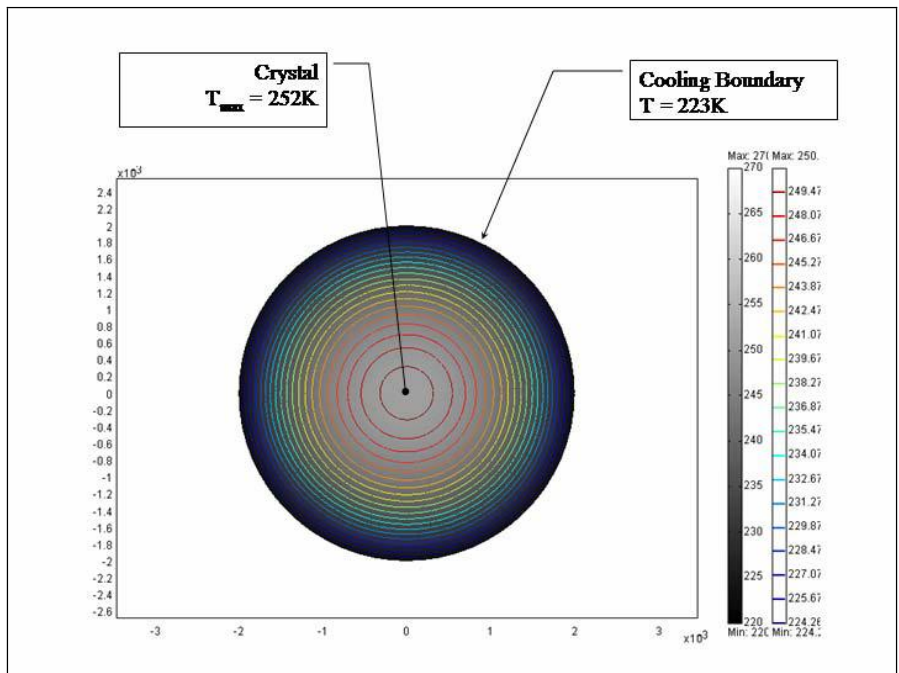


Figure 4

Temperature Distribution: Ideal Thin-Film Evaporative-Cooled Crystal

Comparative Statistics for Both Cooling Technologies

Conductively-Cooled: $T_{\max} = 267K$, $\bar{T} = 254.6K$, $\sigma_T = 11.5K$

Evaporative-Cooled: $T_{\max} = 252K$, $\bar{T} = 237.3K$, $\sigma_T = 8.3K$

The comparative statistics show that the uniform temperature boundary condition produced by the evaporative-cooled configuration results in better overall thermal performance.

Candidate Thin-Film Evaporative-Cooled Flow Geometries

To evaluate the performance of the thin-film cooling concept with that of conductive cooling, hydrodynamic performance must be considered along with thermal performance. For instance, the conductive cooling system is totally passive – requiring no power from the satellite bus. To be a viable alternative, the fluid transport for the evaporative system should take place with the minimum drain on the satellite power bus. This metric is indicated by determining the pressure drop in the liquid film flowfield. Low pressure drops are desirable. If the liquid pressure drop is sufficiently low, then a capillary-pumped loop becomes a viable transport mechanism, requiring no power from the bus to operate.

To date, two axial flow and one radial fluid flow configurations have been proposed. These three configurations have been given the descriptive names: (1) Co-Current Axial Flow, (2) Counter-Current Axial Flow, and (3) Radial Flow. Co-current axial flow (Figure 5) is produced when the liquid and the gaseous states of the coolant are transported in the same direction along the axis of the rod.

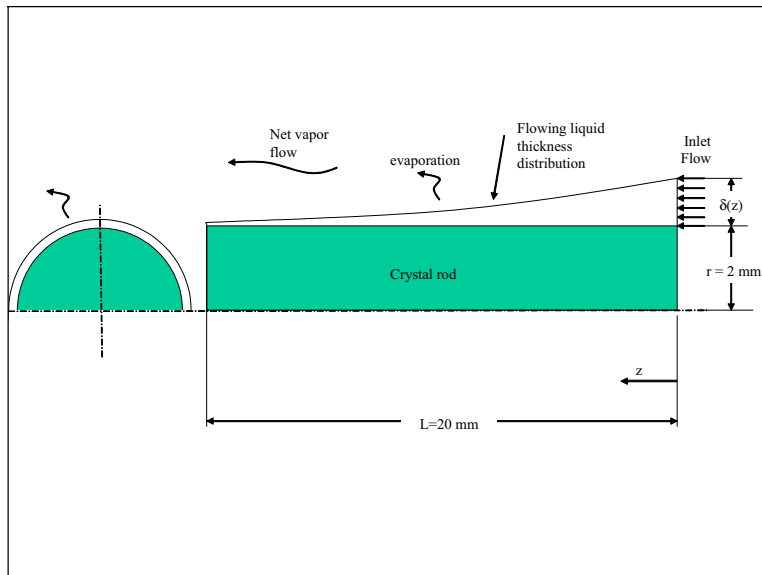


Figure 5

Co-Current Axial Flow

The obvious advantage is that co-current flow minimizes shear forces at the liquid-vapor boundary. A disadvantage is that the entire liquid mass is injected in one end, resulting in either greater film thickness, or greater entrance velocities.

Counter-current axial flow (Figure 6) occurs when the vapor flow is opposite that of the liquid. An advantage of counter-current flow is that the liquid inlet flow velocity, and the vapor exit flow velocities are approximate half of the co-current flow. A disadvantage is that flow from opposing ends must be exactly balanced with the evaporation rate to prevent fluid buildup on the crystal.

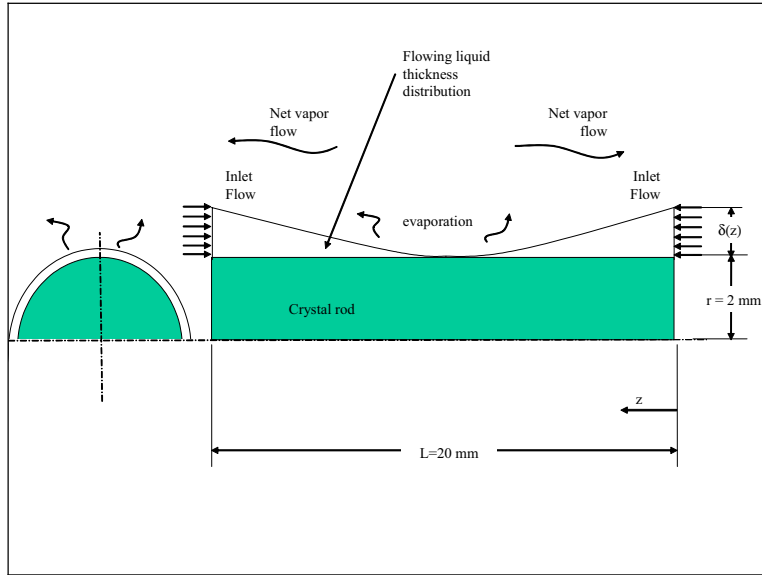


Figure 6
Counter-Current Axial Flow

Radial flow (Figure 7) occurs when liquid is injected at discrete points around the periphery of the crystal. This configuration has the lowest liquid inlet velocities. A disadvantage is that an axial structure is needed along the length of the rod to transport the coolant.

The relationships between inlet velocities and initial film thicknesses for the three subject flow configurations are shown in Figure 8. Note the dramatically lower film thicknesses needed by the counter-current and the radial flow configurations to transport the required coolant mass flow.

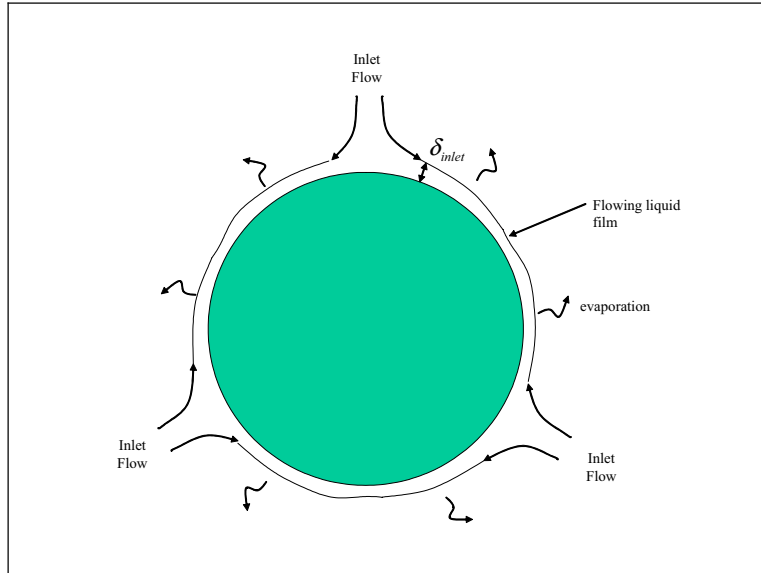


Figure 7
Double-Inlet Radial Flow

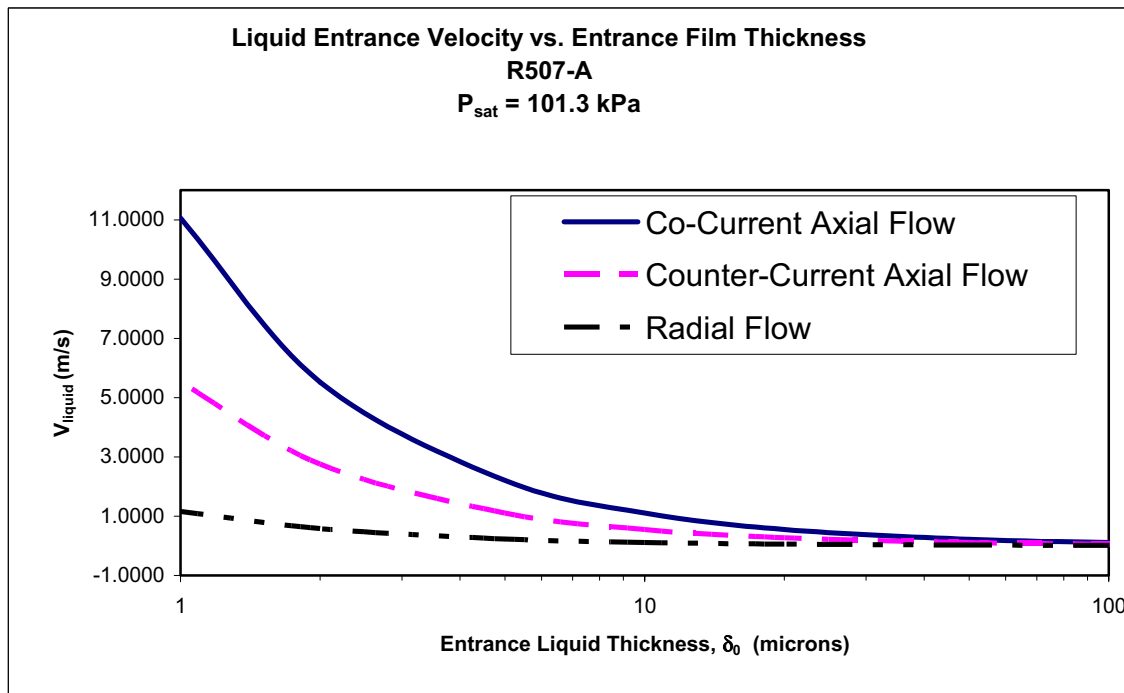


Figure 8
Comparison of Entrance Film Thicknesses for Three Flow Configurations

One-Dimensional Hydrodynamic Study of Axial Configurations

Although the radial flow configuration shows promise based on entrance film thickness, the crosswise flow at the fluid/vapor boundary, coupled with the 2-D inlet flowfield, precludes the use of a 1-D model. Both axial flow configurations, however, are suitable for 1-dimensional, two-fluid model analysis. Such analysis can predict the pressure drop, film thickness distribution, liquid and vapor flow velocities for the different flow configurations by solving a system of ordinary differential equations. Conservation of liquid mass, vapor mass, liquid momentum, vapor momentum and mixture energy equations were solved simultaneously using the given crystal geometry, assuming steady external annular flow, and a 500 micron inlet film thickness [3]. The saturation temperatures corresponding to atmospheric pressure were used in the analysis. Results for the co-current and counter-current axial flow models are shown in Figures 9 and 10 respectively.

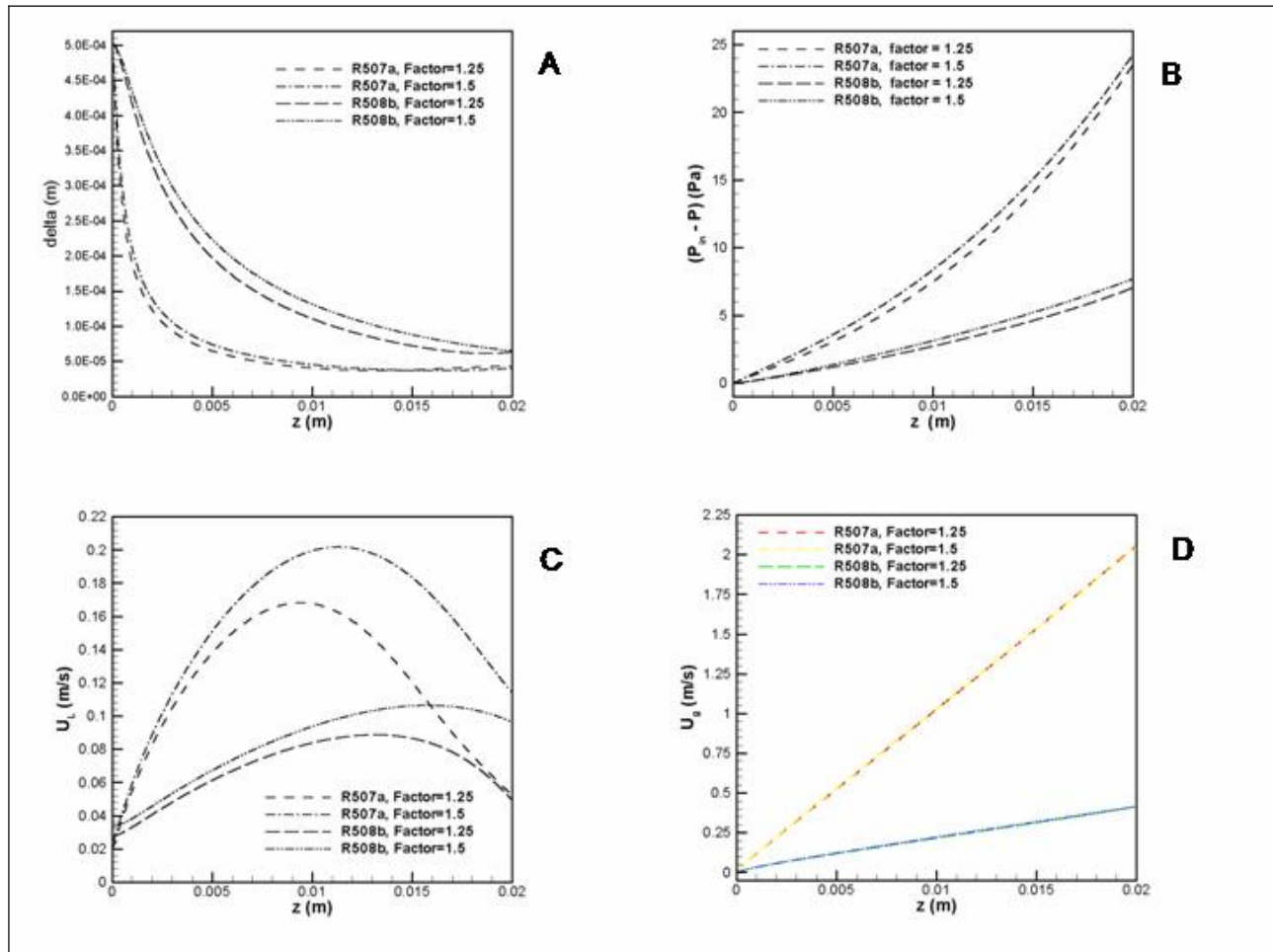


Figure 9

Co-Current Axial Flow 1-D Two-Fluid Model Results [3]

(A) Film Thickness; (B) Liquid Pressure Drop; (C) Liquid Velocity; (D) Vapor Velocity

The hydrodynamic results indicate that very low liquid velocities are required to transport the required coolant. In addition, the small predicted pressure gradients indicate low pumping power requirements.

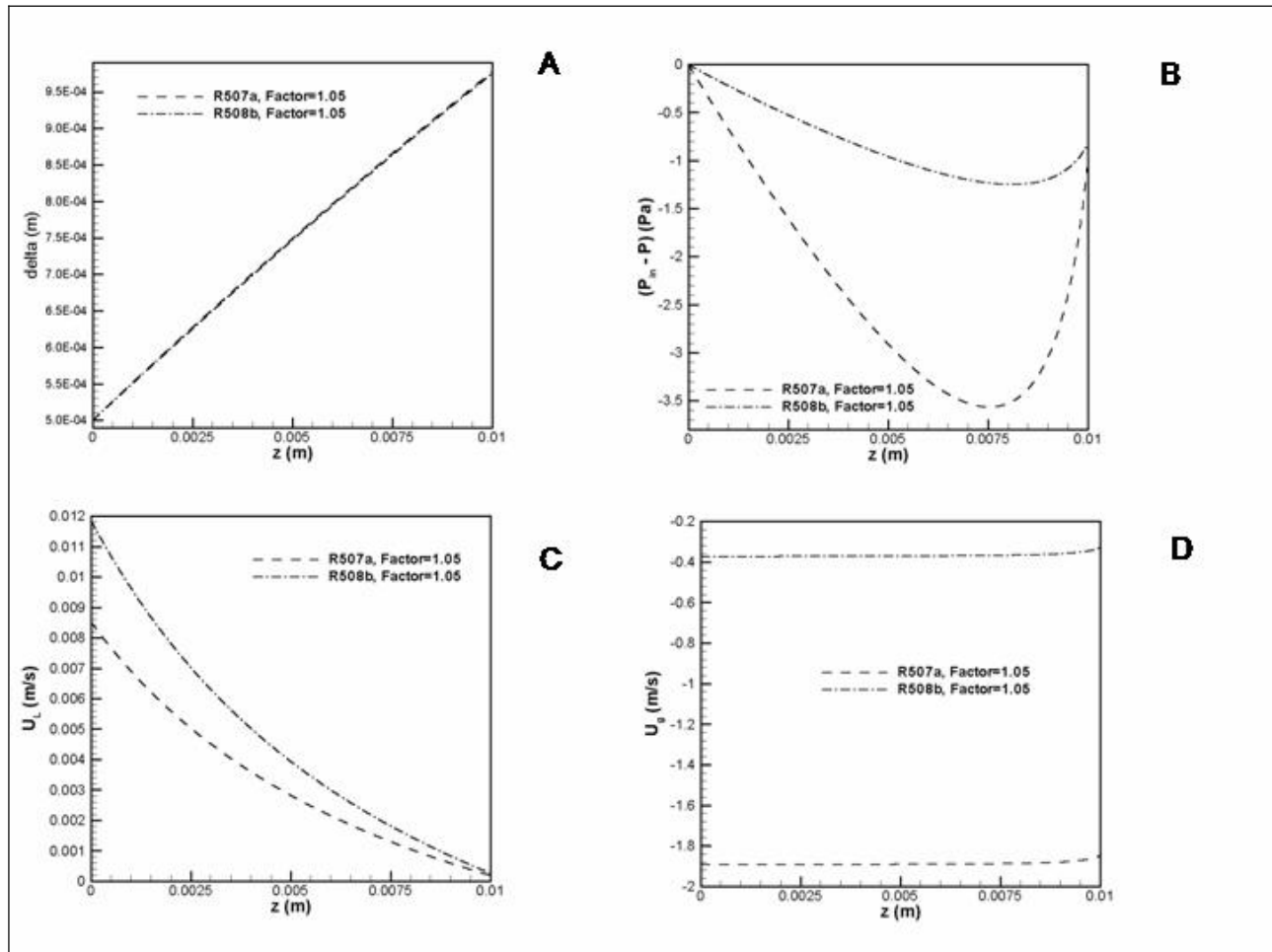


Figure 10

Counter-Current Axial Flow 1-D Two-Fluid Model Results [3]

(A) Film Thickness; (B) Liquid Pressure Drop; (C) Liquid Velocity; (D) Vapor Velocity

Suppression of Nucleate Boiling

One of the requirements for fluid cooling of side-pumped lasers is that the incident diode pump radiation must be transmitted through the cooling medium without measurable attenuation. The formation of bubbles in the film would scatter the incident beam significantly, and is considered a failure mode for the thin-film system. Heat transfer must then take place entirely in the convective evaporation regime, without the onset of nucleate boiling. An incipience model was introduced to determine the critical film thickness needed to support nucleate boiling for the two candidate fluids. The system would need to operate below the critical film thickness, thus providing an upper bound for the film thickness. Figure 10 depicts a graphical representation of the incipience model used. The model assumes the pre-existence of an entrained microbubble. Note that for thin films, the diameter of a bubble is limited by the film thickness. Therefore, nucleate boiling can be predicted by equating the film thickness and wall superheat to promote bubble growth, with the wall temperatures predicted by wall heat convection.

The liquid film superheat required to support bubble growth given a finite-sized vapor bubble as a nucleation site is estimated by Collier [5] by combining the Clausius-Clapeyron equation and the ideal gas law into an equation to predict the wall superheat requirement;

$$(T_g - T_{sat}) = \frac{R}{M} \frac{T_{sat} T_g}{h_{fg}} \ln \left[1 + \frac{2\sigma}{P_f r^*} \left(1 + \frac{v_f}{v_g} \right) \right]$$

The bubble depicted in Figure 11 will not grow unless the liquid film temperature is equal to or higher than T_{sat} .

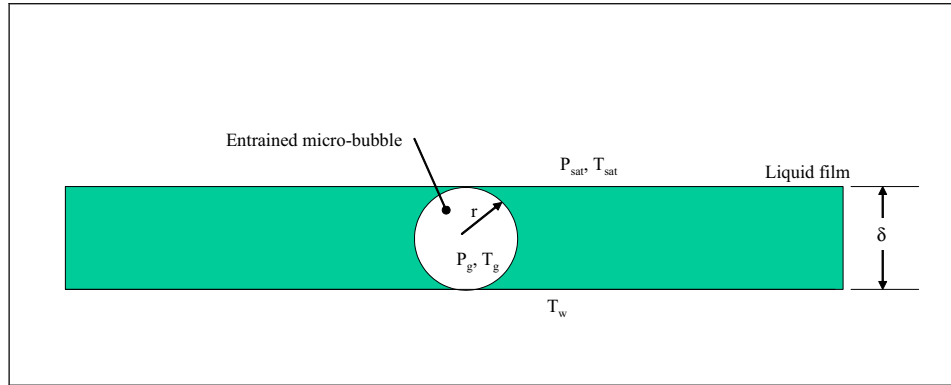


Figure 11
Incipience Model

An analysis was conducted for different saturation temperatures of the two candidate fluids. The results are shown in Figure 12 as plots of wall superheat versus film thickness.

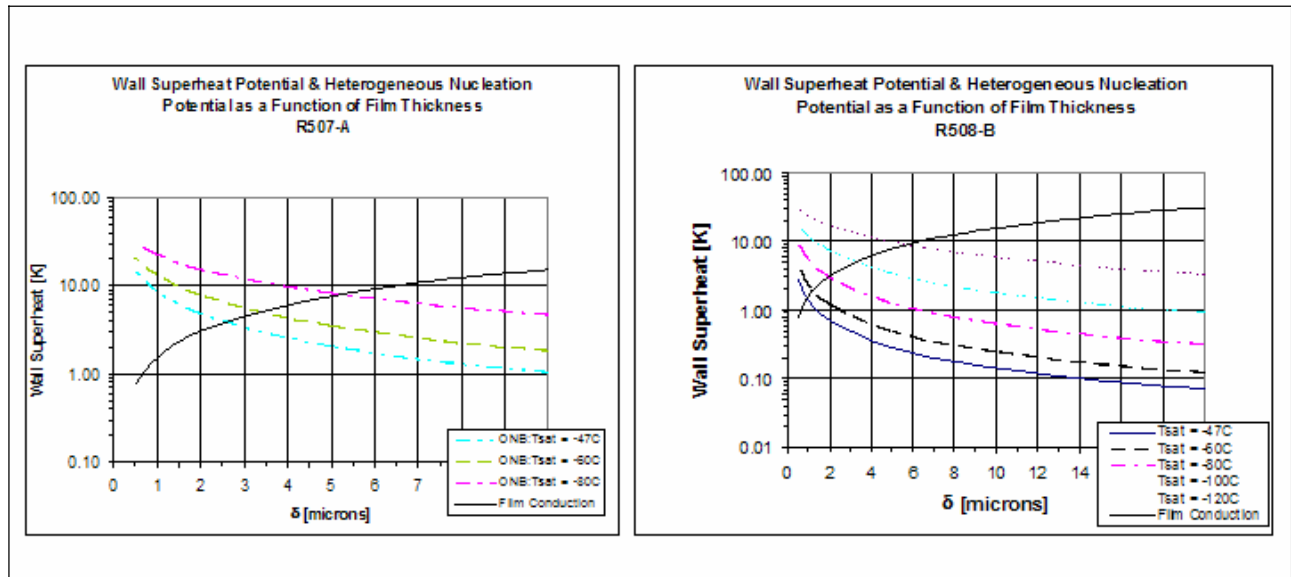


Figure 12
Film Thickness Threshold for the Onset of Nucleate Boiling

Both incipience models indicate that film thickness less than 10 microns may be necessary to ensure the absence of generated or entrained vapor bubbles in the liquid flow. This result supports flow geometries with very thin entrance thicknesses, indicating that the radial flow geometry is worthy of closer examination.

Conclusions

Comparative thermal analyses of the solid domain, and hydrodynamic analyses of the fluid domain support the feasibility of the thin-film evaporative cooling concept for the thermal management of side-pumped laser crystals. Thermal models predict that crystal core temperatures as low as 237K (-36C) are obtainable using commercially available azeotropic refrigerant fluids operating at 223K (-50C) saturation temperatures. Incipience models indicate that film thicknesses below 10 microns may be necessary. The results point to the need to develop three-dimensional flow models to include analyses of radial flow configurations which are more favorable to the production of ultra-thin film entrance flows.

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