Optimization of Spectralon through numerical modeling and improved processes and designs

Bob Y. Chang, Ronald M. Huppe, Christina Chase, Dante P. D'Amato
Labsphere, Inc., North Sutton, NH 03260

ABSTRACT

The demand for progressively more powerful lasers has caused those employing side-pumped laser designs to become acutely aware of pumping efficiency and performance. Additionally, precision applications demand beam stability and uniformity for the lifetime of the laser flash lamp. The use of highly diffuse, high reflectance pump chamber reflectors such as Spectralon®[‡] have been shown to amplify overall power and performance. Spectralon is used in a wide range of side-pumped applications for its superior optical characteristics and design flexibility but stated damage thresholds of approximately 4 J/cm^2 have limited it to lower power applications. To increase energy tolerances, initial damage thresholds are defined through mathematical simulation. A general form of the heat equation is studied numerically to develop a theoretical model of Spectralon's damage threshold. The heat equation is discretized using the Euler method. Secondly, process modifications are performed to test for increased material durability and to physically reproduce initially defined theoretical parameters.

KEY WORDS: thermoplastic, heat transfer, laser cavity, Spectralon, laser pump chamber, pump reflector, laser pump reflector, pumping efficiencies, side-pumped lasers

1. INTRODUCTION

The advent of increasingly efficient laser pumping technologies, such as end pumping and fiber lasers, as well as demand for progressively more powerful lasers has caused those employing side-pumped laser designs to become aware of pumping efficiency and performance. Additionally, precision applications demand beam stability and uniformity for the lifetime of the flash lamp. The use of highly diffuse, highly reflective pump chamber reflectors have been shown to help achieve high power and performance. Spectralon is widely used as a reflector in laser pump chambers for this reason. Its diffuse reflectance of 99% over the range from 300 to 1500nm make it an ideal choice over similar pump chambers made of ceramics or other specular reflectors due to increased efficiency and reduction in hot spots and parasitic oscillations[1].

Spectralon was specially developed as a white reflectance material. In its initial stages of development for use in laser cavities, processes were taken to ensure minimal particulate contamination. Through these steps, a laser-grade Spectralon was developed to withstand a currently specified damage threshold of 4 J/cm^2. While anecdotal information has detailed Spectralon pump chambers being exposed to far higher energy densities, other reports have also described Spectralon burning at lower energy densities. In this paper, a simple heat transfer model is used to give an understanding of Spectralon's thermal viability in a theoretical pump chamber setup. Process modifications are also tested to determine procedures that may isolate sources of damage and also result in increased material durability.

2. HEAT TRANSFER MODEL

To first approximate the pumping chamber environment, a one-dimensional unsteady heat equation[2] in a general coordinate system was used and can be shown as,

[‡] Spectralon is a product of Labsphere, Inc.

$$\rho c_p \frac{\partial T(r,t)}{\partial t} = \frac{1}{r^m}\frac{\partial}{\partial r}\left(kr^m \frac{\partial T(r,t)}{\partial r}\right) \tag{1}$$

where ρ is the density, c_p is the specific heat at constant pressure, k is the heat conduction coefficient, T is the temperature and r and t denote the spatial and temporal coordinates, respectively. The geometric configuration is designated by the exponent m. The value of m in Eq. (1) is either 0 or 1, which represents Cartesian or cylindrical geometry, respectively.

For a complete specification of the equation, Eq. (1) requires the definitions of the boundary and initial conditions. The constant temperature initial condition is,

$$T(r,0) = T_i \tag{2}$$

where T_i is the initial temperature of the entire object. Both constant temperature and convective boundary conditions are considered. These are,

$$T(r,0) = T_{b0} \tag{3}$$

and

$$-k\left.\frac{\partial T}{\partial r}\right|_{r0} + h_0(T(r_0,t) - T_{\infty 0}) = q_0'' \tag{4}$$

where r_0 is the location of the boundary, T_{b0} is the corresponding temperature, h_0 is the heat convection coefficient, $T\infty_0$ is the cooling fluid temperature infinitely far from the boundary and q_0'' is the heat flux into the boundary.

The general geometric and the physical description is presented in Figure 1. Exponent m=1 and $0 < r_0 < r_1$ is appropriate for a cylindrical shell geometry. Heat transfer in a solid cylinder could be studied by setting r_0, h_0, and q_0'' equal to zero. A planar geometry could be considered by setting m equal to 0 in Eq. (1).

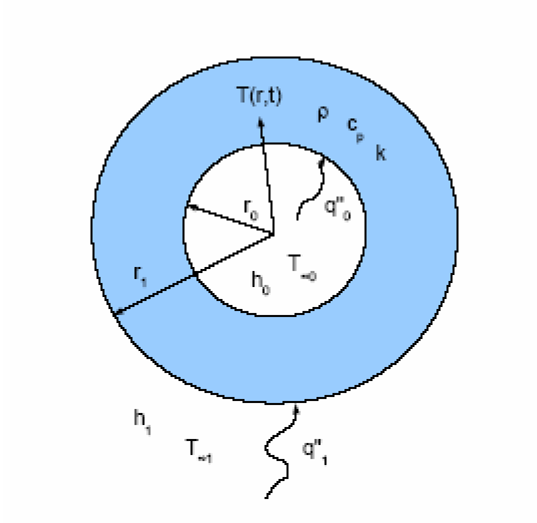

Figure 1: Geometric configuration of the heat transfer model

3. NUMERICAL METHOD

The Euler method was used to obtain a numerical solution for Eq. (1). This method is second order accurate in space and first order accurate in time. The resulting discrete equation is,

$$\rho c_p \frac{T_i^{n+1} - T_i^n}{\Delta t} = k\left(\frac{T_{i+1}^n - 2T_i^n + T_{i-1}^n}{\Delta r^2} + \frac{m}{r_i}\frac{T_{i+1}^n - T_{i-1}^n}{2\Delta r} \right) \tag{6}$$

where n is the discrete time index, i is the discrete spatial index and Δt and Δr are the temporal and spatial resolutions, respectively. Equation (6) additionally assumes a constant value of k. The numerical stability of the Euler method is achieved when,

$$0 < \frac{k\Delta t}{\rho c_p \Delta r^2} < \frac{1}{2} \tag{7}$$

Once the physical parameters and the required spatial resolution for the model are established, the above condition sets an upper limit on the value Δt. However, a typical value for Δt is usually an order of magnitude smaller than this limit, for example,

$$\Delta t \le \frac{1}{20}\frac{\rho c_p \Delta r^2}{k} \tag{8}$$

The convective boundary condition is discretized using a first order forward or backward stencil,

$$-k\frac{T_2^n - T_1^n}{\Delta r} + h_0(T_1^n - T_{\infty 0}) = q_0'' \tag{9}$$

then solved for T_1^n as a function of the interior values of the temperature.

4. APPLYING THE MODEL

An infinitely long cylindrical shell has a cooling water flow inside the inner tube with the same water-cooled exterior. The inner diameter is 2 cm and the outer diameter is 3 cm. The inner cylinder surface absorbs a portion of the energy produced by the laser's pump flash lamp which is operating at a certain pulse frequency. The heat flux (power per pulse) on the inner boundary from the combined energy of the flash lamp and the excited lasing rod may be approximated by multiplying the laser energy in J/m^2 by the pulse frequency in Hz (1/*sec*). This approximation is valid when heat diffusion or convection time is much slower than the rate at which the flash lamp pulse interval deposits energy into the system.

If the diffusion and the convection times were comparable to the pulse interval, then each pulse would need to be resolved temporally by the simulation. The heat convection coefficient[3] is calculated from the Nusselt number (Nu), which is a function of the Reynolds number (Re), is as follows:

$$Nu = h\frac{D}{k} = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{\frac{1}{3}} \tag{10}$$

where *D* is the diameter of the inner cylinder , *k* is the thermal conductivity of the water and Pr is the Prandtl number.

The key parameter in determining whether the structure will cool or heat is the difference between the magnitudes of the convective heat flux and the heat flux. If the convective heat flux at the boundary is initially greater than the heat flux, then the structure will cool from the initial condition. This can also be seen in Eq. (4) because the value of the temperature gradient at the boundary cannot go through a sign change.

All variables stated are summarized in Table 1.

Variable	Units	Description
Simulation Properties		
GEOM	m	Geometric configuration, *m* in Eq. 1
	m	Spatial resultion, Δr
	m	Inner radius, r_0
	m	Outer radius, r_1
	sec	Temporal resolution, Δt
	sec	Final time
Boundary and Initial Conditions		
BCI		Inner boundary condition type, 0-Eq. (3), 1-Eq. (4)
BCO		Outer boundary condition type, 0-Eq. (3), 1-Eq. (4)
TBI	K	Temperature at infintity for inner boundary, or boundary temperature
TBO	K	Temperature at infintity for outer boundary, or boundary temperature
TI	K	Initial Temperature
Physical Properties		
RHO	kg/m^3	Material density, ρ
CP	$J/kg\ K$	Material specific heat capacity, c_p
KC	$J/m\ K\ sec$	Material heat conductive coefficient, k
HI	$J/m^2\ K\ sec$	Inner boundary convective coefficient, h_0
HO	$J/m^2\ K\ sec$	Outer boundary convective coefficient, h_1
QI	$J/m^2\ sec$	Inner boundary heat flux, q_0''
QO	$J/m^2\ sec$	Inner boundary heat flux, q_1''

Table 1: Initialization file parameters.

5. SOLVER COMPILATION AND INITIALIZATION

The discretized equations are described numerically using a FORTRAN90 syntax. The program is a single ready-to-compile code. No additional libraries are required. However, a FORTRAN90 compiler is required. An example of a FORTRAN90 compiler is a non-commercial version of the Intel compiler suite available for download free of charge for a Linux platform from http://www.intel.com.

The code is initialized from the variables in the input file shown in Table 1.

6. SAMPLE CALCULATIONS

If we assume the water temperature is 333.15K (60º C) and the outer temperature is also 333.15 K and then use the density, specific heat capacity and heat conduction coefficients for Spectralon the input file would be:

&SIMULATION_PROPERTIES
GEOM=1,
DR = 0.04,
RI = 0.02,
RO = 0.03,
DT = 10,
TF = 3600
/
&BOUNDARY_INITIAL_CONDITIONS
BCI = 1,
BCO = 1,
TBI = 333.15,
TBO = 333.15,
TI = 333.15
/
&PHYSICAL PROPERTIES
RHO = 1500,
CP = 1000,
KC = 0.25,
HI = 51233.85,
HO = 51233.85,
QI = 4000,
QO = 0
/

The results of the simulation are shown in Fig. 2, which indicate that the structure reaches approximately a steady state solution after 1000 seconds at a temperature just slightly greater than the cooling flow of 333.15K. Under selected conditions, the structure actually cools down from the initial state.

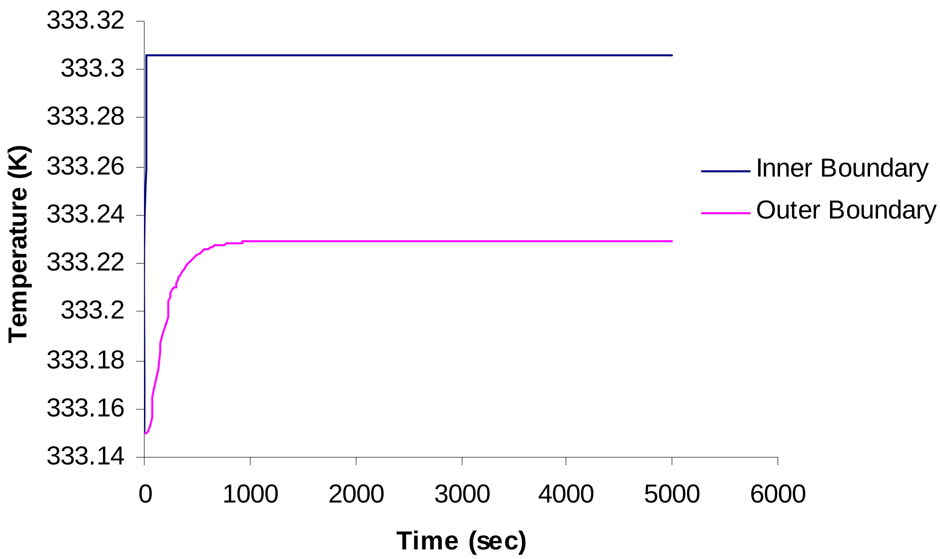

Figure 2: Temperature versus radial distance inside the cylindrical shell for increasing time.

Simulations were also run at 8 J/cm^2 and 15 J/cm^2 (not shown) and the results were nearly identical to the results shown in Figure 2. The temperature in the cylindrical shell will rise from a minimum of 333.15K to a maximum of 333.6K near the boundaries. Even though this is a simple model, it provided initial theoretical parameters demonstrating that Spectralon should be able to easily withstand pump energies of 15 J/cm^2 since it does not decompose until it reaches temperatures above 673.15K.

7. INCREASES IN SPECTRALON DURABILITY THROUGH PROCESS MODIFICATION

Since the theoretical model predicts that Spectralon should be able to withstand any pump energy as long as the cooling system stays active, the next objective was to physically replicate results seen by current users as well as those defined through mathematical modeling. Spectralon pump chamber users have reported reliable performance at $>10^6$ shots at 15 J/cm^2 and even 1KW in ND:Yag lasers. In instances where pump chambers are failing at less than 15 J/cm^2, we look towards contamination on the molecular level since particulate contaminations have been ruled out through fabrication processes. Combinations of cleansing techniques were tested with the theory that increased durability could be found through limiting material variables.

Physical studies were done using conditions comparable to the simulation. Elliptical pump chambers with similar cross sectional areas described in the heat model were tested at various pulse energies in a system for 10,000 shots with a 60ºC flow of 3.5 gallons/min. with tests done before and after modifying the fabrication process.

Energy Density (J/m^2)	Laser Type	# of Shots	Cleaning
4	Pulsed	10,000	None
8	Pulsed	3,000	None
8	Pulsed	10,000	Hexane/Baked
15	Pulsed	1,000	None
15	Pulsed	2,000	Hexane/Baked

Table 2: Damage test results for Laser-Grade Spectralon

In Table 2, results from a combination of cleansing reflectors with hexane followed by vacuum baking the pump chambers prior to deployment in the laser cooling system were tested. As expected, samples tested at the currently specified damage threshold, 4 J/cm^2, easily withstood 10,000 shots without any additional cleaning techniques.

Next, an energy density twice the current specified threshold, 8 J/cm^2, was used. Results showed that the additional purification process provided a 2x increase in durability as treated samples showed no wear after 10,000 shots, seen in Table 2. Untreated reflectors saw a decline in laser efficiency at around 3,000 shots with localized discoloration. Damage in cavities was determined first by a decline in laser efficiency and then further verified by visual inspection.

At nearly four times the currently specified damage threshold, 15 J/cm^2, the onset and rate of discoloration was significantly delayed in the sample. Inspection of the hexane cleansed and baked reflector revealed only localized damage while untreated samples saw a decline at 1000 shots. Once again the cleansing improved longevity at significantly higher energy densities.

The significant increases in durability seen at higher energy densities might indicate that variables leading to lower damage thresholds could initially be molecular contaminants that in an extreme environment could lead to deterioration. Prior studies had also shown that cleaning Spectralon with an organic solvent such as ethanol or hexane followed by vacuum baking[4] reduced the amount of impurities that might degrade under the harsh environment of outer space. Research has reported positive results in improving the damage threshold of Spectralon through boiling samples in deionized water prior to use as well.

Additionally, variables resulting in damage to the cavities may not be isolated only to the cavity itself. Initial tests have reported no damage to Spectralon cavities tested at levels higher than 4 J/cm^2 in gas cooled chambers or chambers isolated by glass tubes with UV-absorbing dopants. This might indicate that after cleaning out Spectralon cavities through chemical and vacuum baking methods, contaminants are newly introduced through the water cooling system. Further testing will need to investigate pump chamber design and its effect on raising pump cavity damage threshold.

8. CONCLUSIONS

A one-dimensional heat transfer model was successfully developed to define initial parameters for the prediction of energy damage thresholds of Spectralon when used as a reflector in laser pump chambers. Significant increases to Spectralon's damage threshold were seen when cleaning with hexane and vacuum baking for 48 hours. Treated samples at energy densities of twice the current limit showed no wear after 10,000 shots and treated samples at nearly four times the limit saw an increase through the deferred timescale in which damage onset occurred which then only showed minor damage to the reflector. Further studies in the combination of cleaning and isolating Spectralon need to be examined to determine the disconnect between theoretical and actual damage threshold possible.

References

1. B. Waldwick, C. Chase, and B. Chang, "Increased efficiency and performance in laser pump chambers through use of diffuse highly reflective materials," SPIE **6663**, (2007).
2. S. Kakac, and Y. Yener, *Heat Conduction* (Taylor & Francis, 1992).
3. W. McCabe, J. C. Smith, and P. Harriot, *Unit Operations of Chemical Engineering* (McGraw-Hill, 2001).
4. J. E. Leland, and A. V. Arrechi, "Phase 2 analysis of Spectralon material for use in on-board calibration systems for the medium-resolution imaging spectrometer (MERIS) " SPIE **2475**, 384-392 (1995).