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THERMAL DISTORTION OF MIRRORS*

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ABSTRACT

Chemical laser mirrors are typically constructed of metal and cooled with water. A chemical laser is capable of generating locally high power fluxes, and the resulting material temperatures can result in severe distortion of the mirror surface. In a typical laser system with a maximum incident heat flux of 0.63 kW/cm^2, a cooled mirror can be distorted sufficiently to change the radius of the reflecting surface from an unheated value of two meters to a heated value of three meters. This change can be compensated, in part, by reducing the initial radius and by modifying the structure of the mirror. This paper will describe the analytical techniques which were used to develop the engineering design specifications for water-cooled mirrors.

The thermal and structural analyses were accomplished by the use of finite difference and finite element computer programs to generate the element arrays, calculate the temperature profiles, and determine the structural deformations. The temperature distribution was calculated using TCAL, a heat conduction program used on a variety of two- and three-dimensional heat transfer problems. The elements were defined by a two-dimensional preprocessor and a special program to link the two-dimensional layers into a three-dimensional array. A mesh generator was used to supply the element array for NASTRAN by which local displacements in the mirror were calculated. The displacements of the reflecting surface elements were then used to determine equivalent radii of curvature for development of design specifications.

This work was undertaken as part of the Corporate IR&D program.

INTRODUCTION

An analytical study was made to evaluate the thermal distortion of mirrors used in experiments conducted at United Technologies Research Center (UTRC) in high energy chemical laser systems. The mirrors act as optical feedback elements of an oscillator. Typically, two highly reflective (> 98% reflectivity) mirrors are aligned to form an oscillator, or cavity, in which a laser medium is contained. A

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laser starts by virtue of spontaneous emission by excited molecules in the cavity, randomly distributed in all directions. The small part of this emission that has a direction of propagation perpendicular to the mirror surfaces stays in the cavity and provides the initial source for stimulated emission of other excited molecules. Upon successive reflections by the mirrors, the radiation traveling through the laser medium is coherently amplified. The radiative flux within the cavity increases until an equilibrium is reached in which the rate of production of energy through stimulated emission equals the rate of loss of energy.

Energy can be lost by absorption in the mirrors, scatter out of the cavity by imperfections in the mirror surface, or scatter by distortion of the mirror surface. Essentially all of the energy extracted from this type of laser oscillator, referred to as a closed cavity, is obtained by the calorimetric measurement of energy absorbed by the mirrors. If the mirrors distort due to the thermal loading imposed upon them, the attendant scatter of energy out of the cavity will result in a loss in indicated power produced by the laser medium. This condition may be obtained for thermal loadings much below those for which any structural damage occurs.

An analytical study was made to investigate the distortion that may be obtained for representative laser conditions to which mirrors of a design originated by Aerospace Corporation[1,2] were subjected in tests conducted at UTRC. The results of this analytical study are reported in this paper.

ANALYSIS

The mirror that was analyzed consists of a rectangular block with the reflecting surface cooled by water. The water temperature rise is a measure of the heat absorption which is equivalent to laser power generation in closed cavity configurations. In many experiments, the run duration is very short (less than a minute), and if the heat was allowed to bypass the water and soak into extraneous metal structure, severe problems

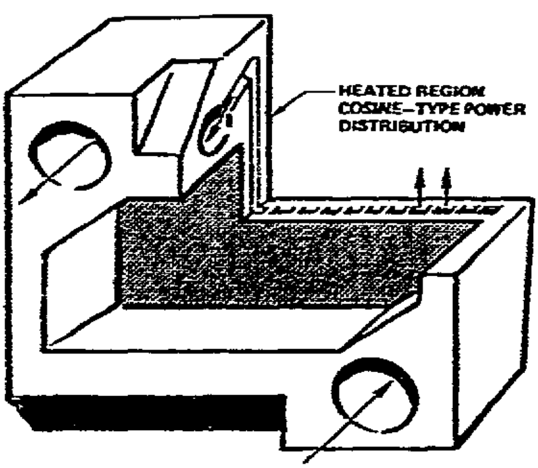

Fig. 1. Diagram of laser mirror.

with power generation measurement would be encountered. Therefore, the block is hollowed out on the side opposite the reflecting surface. A diagram of the mirror structure is contained in Fig. 1.

The distortion of the mirror was determined by first calculating the temperatures in the mirror using a heat conduction computer program. The obtained temperature distribution was input to a structural analysis computer program which provided a detailed map of local displacements throughout the mirror.

Thermal analysis

The heat conduction computer program, which is called TCAL, was formulated at Pratt and Whitney Aircraft and is in general use throughout the divisions of United Technologies Corporation. In the program, the heat conduction equation, a time-dependent version of Laplace's equation, is written in the form of finite difference equations. These equations are solved by a relaxation technique within selected convergence criteria to obtain either steady state or transient solutions. The input to the program consists of a description of the model of the hardware being analyzed, the material properties, the convective and radiative properties of the model, the properties of the fluids used within the model, and the heat generated on the surface or within the model.

In fine detail, the conduction heat transfer model consists of an array of rectangular solids called nodes which are linked together to form suitable conduction paths. Many of the geometric input details such as the dimensions of the nodes, the

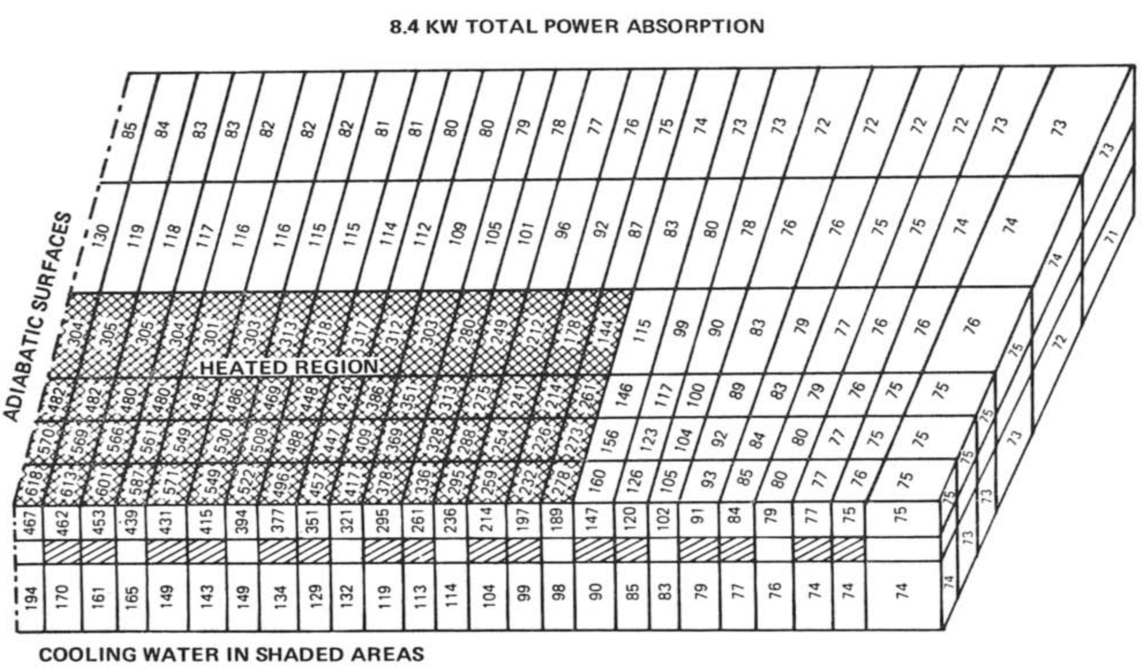

Fig. 2. Temperature distribution in laser mirror in F.

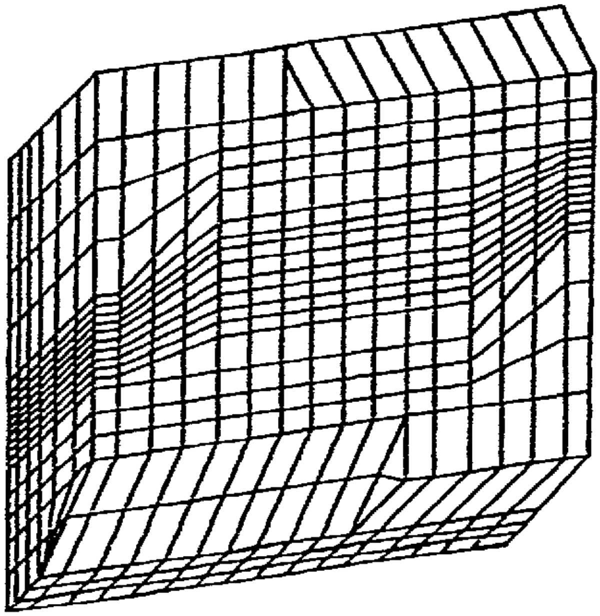

Fig. 3. Laser mirror structural model.

conduction lengths, and the connecting areas are calculated by a preprocessing interactive computer program called GOB which converts coarse model dimensions into fine model details.

As shown in Fig. 2, the size of the array is kept to a minimum by dividing the model at adiabatic surfaces which for this configuration are also planes of symmetry. Also shown in Fig. 2 are the outlines of the nodes and the temperatures that were calculated for each node at steady state operating conditions. These temperatures served as input to the structural analysis computer program.

Structural analysis

The structural analysis program, which is called NASTRAN, was formulated at the National Aeronautics and Space Administration (NASA) and it is widely used in industry to solve problems in the elastic strain regime. In the program, the stress–strain curve is integrated to determine strain energy. The strain energy integral is minimized at selected points in the structure.

The input to the model consists of a description of the model of the hardware being analyzed, the material properties, the constraints on motion at surfaces or edges, and the temperature distribution previously mentioned. The constraints on motion can be imposed either by physical boundaries such as mounting arrangements or by artificial means designed to keep the model from becoming induced into rotating or translating motion during the calculation.

In fine detail, the structural model consists of an array of hexahedrons called elements which are linked together to transmit loads. The energy integral is minimized at various corners and edges of elements to obtain the solution in terms of stresses

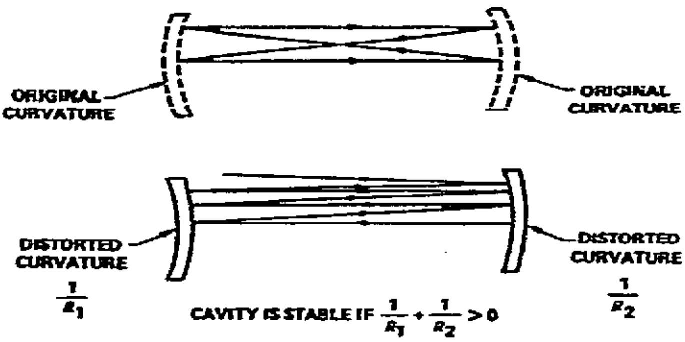

Fig. 4. Cavity stability criterion.

and displacements. Many of the geometric input details such as dimensions of the elements and their interconnections are calculated by a preprocessing interactive computer program called MARCMESH which converts coarse model dimensions into fine model details.

As shown in Fig. 3, the full model was used in the structural element array because planes of zero stress were not expected to be present in the solution. Although some of the elements appear to be triangular prisms in the diagram, they were actually truncated to trapezoidal cross-sections in the input.

Distortion limits

To obtain valid closed cavity tests of chemical lasers, it is necessary that mirror distortion be sufficiently low to minimize the scatter of radiation away from the calorimeters which measure the power. The upper limit on distortion is the amount that makes the cavity unstable. The instability condition can be explained by considering the radiation flux in discrete beams. In a closed cavity of highly reflective, convex mirrors, a beam would be expected to undergo approximately 50 reflections before all of its energy is absorbed. As shown in Fig. 4, a beam within a cavity with slight misalignment can leave the cavity after only a few reflections if the combined mirrors have a net convexity. Thus, if a pair of mirrors become convex because of distortion, an appreciable loss of energy can be caused by beams being reflected out of the cavity. The condition for stability is stated as follows.

$$\frac{1}{R_1}+\frac{1}{R_2}>0 \tag{1}$$

where R_1 is the heated radius of one mirror and R_2 the heated radius of the second mirror.

Results of analysis

The results of the analysis indicated that the distortion level in the beryllium copper mirror reached almost 0.005 in. as shown in Fig. 5 by the vertical displacement of the hot surface. Not only did the hot surface expand relative to the cold surface

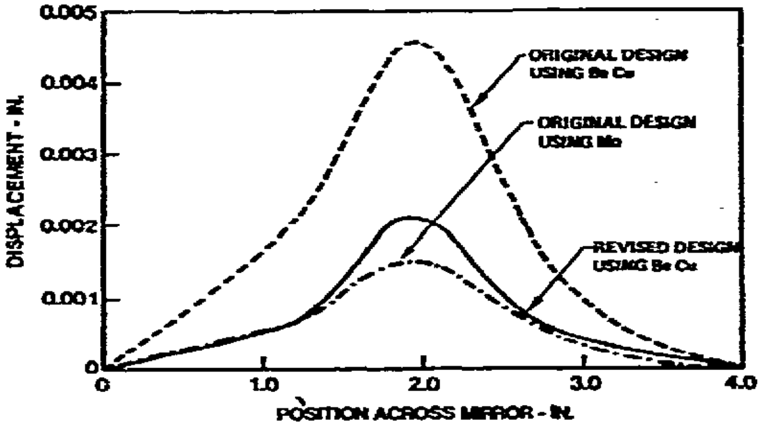

Fig. 5. Maximum distortion of mirror surface.

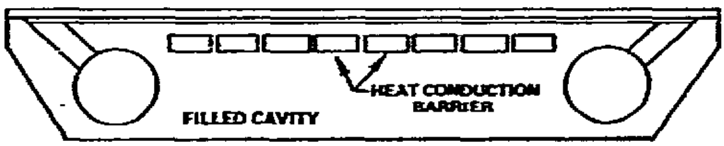

Fig. 6. Improved thermal design.

because of its temperature level, but the expansion caused a curling effect which manifested itself in horizontal displacement of the edges of the cold flanges. The flanges moved toward each other 0.0015 in. in one location.

Although the actual values of distortion seem very small, they are high enough to cause unacceptable optical errors. While the sum$(1/R_1) + (1/R_2)$ was $+0.375$ at a cold condition, it was calculated to be -0.531 during heating.

The analysis was extended to include a material change to molybdenum which has a thermal conductivity similar to beryllium copper and a much greater stiffness. The distortion was considerably reduced as shown in Fig. 5 and the sum$(1/R_1) + (1/R_2)$ was calculated to be $+0.179$ during heating. Because of the high cost of molybdenum fabrication, a modification to the design was made in the hope that beryllium copper could be used as the material. The mirror was stiffened by adding a back plate which made the structure nearly solid and increased its overall thickness. Small spaces were left in the wall to suppress heat conduction from the reflecting surface into the thick, solid structure. A diagram of the new model is shown in Fig. 6. The analysis indicated that the distortion was considerably less than in the original design and the sum$(1/R_1) + (1/R_2)$ was calculated to be -0.102 during heating.

As a result of the analysis, two new mirrors were constructed. One of the mirrors had the essential features of the original beryllium copper mirror except that it was made of molybdenum. The other mirror was made of beryllium copper and it had a thick solid structure which was thermally isolated from the cooling water. Initial tests indicated that the laser power measured with the new mirror was approximately 50% higher than the power obtained with the original design. Measured power with the revised beryllium copper mirror did not show an improvement over the original design.

CONCLUSIONS

The computer programs available for thermal analysis can be used to supply useful information regarding the thermal behavior of calorimetric devices. When the thermal analysis is coupled to a computer program for the calculation of stresses and displacements, the structural behavior of the devices can also be described in detail. The work that was performed on the chemical laser mirror supplied considerable information on the power loss mechanism of the experimental laser. The results were used to make changes in the mirror that considerably improved the mirror performance.

REFERENCES

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