Thermal Modeling of Cryogenic Accelerator Structures*

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Abstract

A software package has been created for examining the thermal behavior of cryogenic particle accelerator structures. It models the steady state heat flows in waveguides and beampipes while in operation, treating both diffuse and specular infrared reflection. The programs runs effectively on small computers, since only a few simple geometries are treated, and the output display options are limited. Overall accuracy for simple test cases is on the order of a few percent, but on short structures with very wide apertures the errors can be up to 10%. An analysis of radiative heat load in the B-factory cavity is presented, and thermal management strategies for the input waveguide are discussed.

I. INTRODUCTION

Early in the design of the B-factory test cryostat, it was recognized that some features of the cavity would make the design of a low heat leak system a challenge. Specifically, the relatively large beampipe (240 mm diameter) and input waveguide (100mm x 430 mm) could allow a significant amount of infrared radiation into the cavity, and thus introduce a large heat source into the helium coolant bath. Further thermal study was warranted, but no simple analytical technique could treat both specular and diffuse radiative heating, as well as RF heating, wake field heating, and conduction. Sophisticated finite element codes, such as COSMOS/M[1], were capable of such analysis, but for this task, they would have required too large and investment of time and resources to be cost effective. A software package was developed at Cornell to conduct thermal modeling of accelerator structures. This package, called ASTModeler, provides an inexpensive and useful tool for accelerator design.

II. PROGRAM DESCRIPTION

To make this software package easy to use, a number of compromises were incorporated into it from the beginning. First, only simple geometries can be accommodated, either cylindrical or rectangular pipes. This avoids the problems of specifying and meshing complex shapes, but still allows the treatment of many structures commonly found in particle accelerators. Because of this restriction on the model geometry, it is also possible to limit the output to simple two dimensional plots without any loss of information. A line oriented input section prompts the user to describe the modeled section in terms of the following parameters:

- Geometry- rectangular or cylindrical
- Size- length and aperture
- Temperature- endpoint temperatures
- End conditions- open, reflective, or black body
- Material- 304 SS, Cu, Al, or Nb
- Plating- material and thickness
- Surface finish- roughness
- RF environment- frequency and power level

Heat exchangers can also be specified for the section, in terms of tube size, shape, thickness, material, and gas flow rate.

The material data necessary to perform radiative and conductive heat transfer calculations are stored in a library which can be expanded to accommodate any additional materials of interest. Most of these data are available from published literature, but some are not. For example, to accurately treat specular radiation, it is necessary to know both the diffuse reflectivity and specular reflectivity of the material concerned. The data is not available for niobium, the material used in superconducting cavities. This motivated a series of optical measurements on unpolished niobium[1]. The results of this study, which are incorporated in the material properties database contained in ASTModeler, were that niobium has an emissivity of .05, and that it is constant for all wavelengths from 5 μm to 20 μm. In addition, the specular portion of reflected energy varies smoothly from 85% at 5 μm to over 95% at 20 μm.

III. COMPUTATION TECHNIQUES

The computational package has three main parts; a conduction solver routine, a radiation solver routine, and an additional routine which incorporates RF heating calculations and heat exchanger cooling calculations.

The conduction routine is the starting point of the program. Because of the simple geometry, the conduction problem reduces to one dimensional formalism. This routine segments the model structure and then applies a finite difference form of Fourier's law to these segments. The net heat flow into each segment is calculated by summing the heat flows from the adjacent segments, as well as an external heat flow determined by other routines. In the steady state, all segments but the end ones should see no net heat flow. Each segment temperature is perturbed to see whether this causes an improvement or deterioration in the segment heat balance. This effect is used to estimate the temperature adjustment necessary to balance heat

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[1] COSMOS/M is a registered trademark of Structural Research

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flow through the segment. The iterative adjustment process is stopped when total heat flow for all segments are balanced to some small fraction of the heat flow to an adjacent segment. This convergence criterion is adjustable, and is usually set to a fraction of a percent. With a convergence criterion of 0.1%, this routine agrees with analytical results to within 2%.

The radiation routine uses the segments defined in the conduction routine to define a set of surfaces interacting through radiation and absorption. These surfaces define a greybody enclosure, with temperatures set by the results of the conduction routine. As with the conduction problem, in steady state, the heat flow to and from any surface balance. The problem can be expressed and solved in matrix form through the use of view factors, or geometrical factors quantifying the degree to which radiation from one surface impinges on another. The calculations of these factors is difficult in the general case, especially when specular reflections are considered [2]. These calculations become merely tedious in the simple geometries considered by ASTModeler, and they need only be performed once for each model. The most elaborate of these calculations involves the interaction between the end plates of the model enclosure, and the truncation of this series creates the largest error in the radiation routine. For models in which this end to end interaction is large, as for a short, large aperture beampipe, the disagreement between calculations and analytical results[3] can approach 10%.

The last routine contains the formulas necessary to calculate RF heating in model structures, as well as a heat exchanger modeler. The RF heating formulas[4] incorporate the effects of anomalous skin depth in conductors[5] and of BCS surface impedance in superconductors[6]. The heat exchanger routine determines the heat conducted from each segment to the gas passing through the cooling tube attached to that segment. A boundary layer thermal resistance is calculated from fluid Reynolds number, and the series combination of that and wall thermal resistance determines the effective resistance from segment to cooling gas.

The three main routines are executed in series, with the conduction routine determining a trial solution for segment temperatures. Those temperatures are used by the radiation routine to determine radiative heat fluxes for each segment, and by the third routine to calculate any heat flows in, from RF heating, or out, from heat exchanger cooling. The calculated external heat flows are then returned to the conduction routine, and temperatures are altered until the heat flows are again balanced. The process is iterated until adjustments become negligible.

IV. DESIGN EXAMPLES

One of the first problems examined with this package was the heat load presented by the B-factory beampipe. Since the cavity connected to that beampipe was not cylindrical, a cylindrical structure with the same thermal properties as the cavity had to be specified. This was done by using a 2-D Monte Carlo simulation of the behavior of infrared rays propagating in the beampipe and cavity. Each ray was launched from one aperture with a direction determined by a Lambertian weighted random number generator. The ray then experienced either specular reflection or complete absorption at every boundary collision, with absorption probability equal to the boundary emissivity. The simulation indicated that the cavity absorbed more infrared radiation than the beampipe, due to multiple reflections from its concave surface. This absorption pattern could be simulated by a cylinder with a darkened region (lower reflectivity) at the cavity location. The model shape, with an 85% reflectivity in the darkened region and 95% reflectivity elsewhere, was used in ASTModeler to make further thermal calculations. These calculations indicated that the total heat load due to radiation from 300K surfaces was 10.4 W, with another 10.3 W due to conduction along the walls of the beampipe. Since the black body radiation through both beam ports was calculated to be 40 W, it is clear that most radiation simply passed through the cavity without causing heating.

A similar analysis was conducted on the input waveguide bringing RF power into the cavity. In this case, since the rectangular waveguide was terminated by a coupler at the cavity end, much of the IR radiation was absorbed in regions cooled by liquid helium. For mechanical reasons, it was necessary to have two 90 degree E-bends in the waveguide, so it was decided to cool the bend most distant from the cavity to low temperatures with liquid nitrogen. This avoided a line of sight path from room temperature structures to cryogenic ones, but ray tracing simulations indicated that nearly 15 W of radiant energy would be delivered by reflections off the waveguide walls. In fact, the waveguide made an effective light pipe for infrared radiation, due to the high reflectivity of niobium. This effect was controlled by putting small steps inside the waveguide elbow. In both simulations and optical experiments on scale models, nearly 90% of incoming radiation was reflected back to its source, while in ungrooved elbows, less than 3% was returned.

Analysis of this revised waveguide design indicated that 17.2 W would still be conducted into the helium coolant, and that as much as 12 W of this was from RF heating of the waveguide section between the cooled (80K) elbow. This, when added to the heat loads already calculated for the beampipe, was more than allowed by the refrigeration budget. Thus, it was decided to incorporate a helium gas heat exchanger on the waveguide section between the two E-bends. The optimization procedure required a large number of calculations involving various cooling tube geometries, sizes, and flow rates. Semi-circular channels were selected over simple tubes because they exhibited much better heat transfer properties. Rectangular channels were as good as semi-circular ones from a heat transfer standpoint, but they were rejected because of assembly difficulties. Studies of cooling as a function of gas flow rate indicated that the optimum flow was about 50 mg/s of helium vapor. At this flow rate, total conduction along the waveguide was 3.9 W, an acceptable figure. Additional flow did provide more cooling, but the marginal improvement did not compensate for the reliquification cost of the warmed helium.

V. REFERENCES

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