Cryostat Modeling for the Superconducting Interaction Region Magnets: CESR Phase III

Charles M. Payson

Battle Creek Central High School, Battle Creek Public Schools
Battle Creek, MI 49017

Abstract

Part of the upgrade to the CLEO III particle detector involves the installation of new superconducting quadropole magnets on either side of the interaction region. In order to keep cryogenic cooling costs down, a heat load analysis of the of the cooling system is necessary to predict which heat loading parameters most greatly affect the system, and how changing the heat loads changes cooling system performance. This problem was addressed by performing the necessary engineering heat transfer calculations and putting them together in spreadsheet format. Spreadsheets were chosen so that as the design of the cooling system changes, modifications to the analysis can be made swiftly and accurately. In addition, the spreadsheet can be easily updated as new or unforeseen conditions warrant. This format allows the user to perform an analysis of the system by using a laptop computer on location and in real time.

Introduction

The CLEO III particle detector upgrade is part of the ongoing high energy particle research activities at the Cornell Electron Storage Ring (CESR) on the campus of Cornell University. The upgrade from CLEO II to CLEO III provided an opportunity to improve chosen sections of the CESR accelerator as well. One of these improvements was to install new superconducting quadropole magnets on either side of the interaction region in order to increase the luminosity of the machine. The replacement magnets would need a new cryogenic cooling system specifically engineered to cool this particular design. Liquid helium as a cryogenic medium is expensive ($10,000/Watt/year) [1], and a calculated heat load on the system is usually performed in order to predict operating costs, point out problems with the design, and to provide clues to future improvements in the cooling system. Charles M. Monroe of Monroe Brothers Ltd. had previously performed a heat load analysis, but this was when the design was still in its infancy. Since significant modifications in the design had occurred during its progress, another analysis was needed that would reflect the current configuration.

Schematic

Before characterization of the system could proceed, the various types of heat loads to which the cryogenic system will be subjected must be identified. Since engineering drawings can provide too much detail and spread the design information over several drawings, a schematic of the cryogenic system is made as a way to collect all of the relevant information and display it on one diagram. The drawing in Fig. 1 is an example of an engineering drawing that provides too much detail, and yet leaves out other critical details that are posted on different drawings [2]. While useful in determining dimensions and materials, it is not useful in a heat transfer analysis.

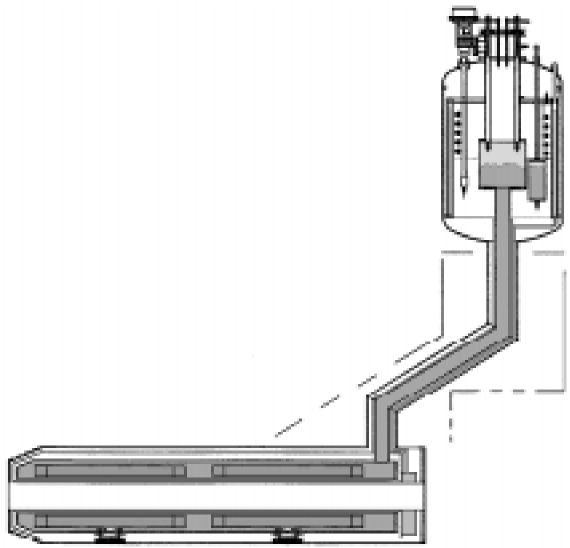

FIGURE 1. An example of an engineering drawing of the cryogenic system. The pre-cool box is in the upper right, connected by the feed pipes (or umbilical) to the cryostat underneath.

The schematic derived for this particular application is shown in Fig 2. While not dimensionally accurate, it provides only the information necessary for the heat load analysis and does it using a single figure. From this diagram heat loads were identified and analyzed.

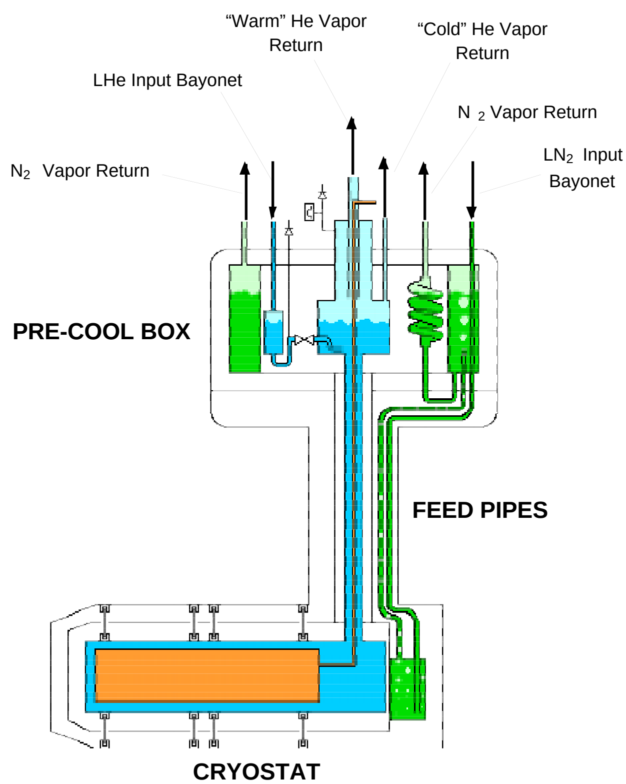

FIGURE 2. The final diagram used for the analysis of the heat loads. Note the addition of carbon fiber straps used to support the liquid helium vessel in the cryostat (8 out of 16 shown).

Characterization

Since the liquid helium and liquid nitrogen used in the cryogenic system are not in significant motion, heat transfer by convection is virtually nonexistent in this system. Conduction and radiation are therefore the main energy transport modes. The basic conduction equation used for cryogenic heat transfer is

$$q = \frac{A}{L} \int k \, dT \tag{1}$$

where A is the cross-sectional area of the heat transfer conduit, L is the length of the conduit, and the integral of $k \, dT$ is the integrated thermal conductivity of the material over the temperature range in question [3]. The values for integrated thermal conductivities of various materials at cryogenic temperatures has been the subject of much research in years past, with the values for materials used in cryogenic systems reasonably well known [4].

The Stefan-Boltzmann equation for radiation heat transfer between blackbodies is

$$q = \sigma A \left(T_1^4 - T_2^4 \right) \tag{2}$$

where σ is the Stefan-Boltzmann constant [5], A is the area of the radiant surfaces, and T is the temperature of each surface. Cryogenic systems are not blackbodies however, and Eq. (2) must be modified to take into account true surface emissivities and geometric shape considerations. If heat flow is viewed as a "current", then the heat transfer can be viewed as being an energy potential difference divided by the sum of the surface resistances to radiation. The Stefan-Boltzmann equation becomes

$$q = \frac{\sigma \left(T_1^4 - T_2^4 \right)}{\sum R \, (\varepsilon, A)} \tag{3}$$

with R being a function of the true surface emissivities ε and geometric shape factors A. Eq. (3) permits the use of a analysis technique known as the resistor network method [6], a technique analogous to electric circuit analysis where Kirchhoff's current laws can be used to solve for the heat transfer anywhere in the network [7].

Use of this method on different parts of the cryogenic system revealed a simplified method for performing heat transfer studies on this type of system [8]. By dividing the right hand side of Eq. (3) by the surface area of any part of the system containing liquid helium, a constant value is obtained [9]. This could be called an equivalent heat load coefficient, h. This allows a much simpler method for determining the radiation heat transfer of systems of this type

$$q = SA \cdot h \tag{4}$$

where SA is the surface area of the liquid helium container. A value for the equivalent heat load coefficient had been used in a previous analysis [10], and verification of this value allowed the use of Eq. (4) in all subsequent radiation calculations.

Results

A spreadsheet suitable for use on a laptop computer containing the calculations for the total heat load on the cryogenic system has been developed and has been through preliminary testing. The first worksheet (page) of the spreadsheet can be seen in Fig. 3. This is a summary page containing the results of calculations performed on subsequent worksheets. Along with the summary information is another simplified diagram of the cryogenic system. Input values to account for changes in the design or materials may easily be changed on the calculation worksheets and will be reflected automatically on the summary worksheet. Any as yet unidentified heat loads on the cryogenic system may be added to the calculation worksheets without affecting the calculations on the existing heat loads.

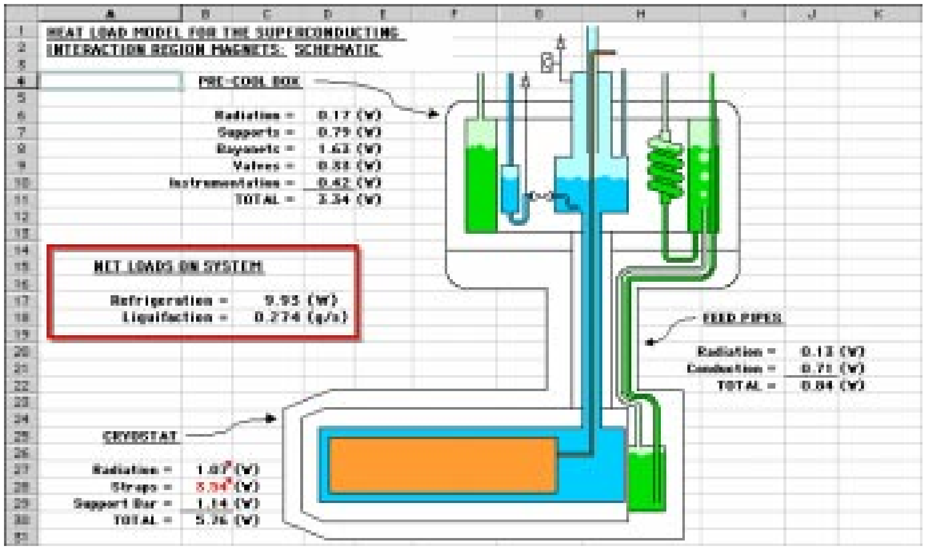

FIGURE 3. The summary worksheet of the working spreadsheet document.

Conclusions

This model of the cryogenic system will have to be tested thoroughly by comparing its results with the actual cryogenic system when installed and operating. Modifications to the model can then be proposed and evaluated when there is actual data on the operation of the system.

The most critical thermal loading on the cryogenic system is conduction to the cryostat liquid helium vessel (at 4˚K) from the outer tube of the cryostat (room temperature) through the carbon fiber straps used to secure the liquid helium vessel in place. Since the thermal conductivity and tensile modulus are directly related [11], the carbon fiber straps will have to be chosen carefully to minimize the thermal conductivity without sacrificing the required mechanical properties. One option (if possible) to further reduce the heat load through the straps would be the addition of “thermal intercepts” [12], pieces of highly conductive material (such as braided copper) bonded to the liquid nitrogen-cooled shield at one end and bonded to the carbon fiber strap at the other end, as close to the room temperature end of the strap as possible. This would lower the temperature gradient at the “cold” end of the strap, thereby reducing overall heat transfer.

Acknowledgments

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Footnotes and References

1. This is an estimate according to a discussion with J. Welch.
2. This is a breakout view of a drawing of the cryogenic system provided by Tesla Engineering Limited.
3. From Holman, J.P. Heat Transfer.
4. From Cryogenic Data Guide. AS Scientific Products Ltd.
5. $\sigma = 5.67 \times 10^{-8}$ W/m$^2\cdot{}^\circ$K^4
6. Developed by A.K. Oppenheim (see next footnote)
7. From Holman, J.P. "Radiation Heat Transfer." Heat Transfer.
8. "This type" being a liquid helium vessel surrounded by several wrappings of superinsulation, a liquid nitrogen-cooled shield at 77˚K, and an outer tube at room temperature (300 ˚K).
9. This constant value is 0.28 W/m^2.
10. That value was 0.3 W/m^2, on an analysis performed by Charles M. Monroe.
11. From paper by Reed and Golda.
12. From paper by Watts, Boulios, Hartwig, and Huson.

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