Thermal Analyses of the Intermediate Station of the Cryocooler-Cooled MICE Coupling Solenoid

Alexey Radovinsky, Alex Zhukovsky

***Abstract*— The MICE coupling coil is conduction cooled using 3 cryocoolers, which maintain an operating temperature of about 40 K and 4.5 K at the first and second stages respectively. The analyses account for the balance of heat loads at the intermediate cooling station integrating 3 cryocoolers on 3 copper plates connected by 2 pairs of copper joint straps, and 2 copper blocks with the terminals for the optimized RT and HTS current leads. Each cryocooler's cooling power is a function of the temperature of its first and second stages. Temperatures at the first stage of individual cryocoolers are different. Temperature drop between the cryocooler first stage and Cu lead cold end is calculated by FEA performed using TEMPO, a thermal package of the Vector Fields Opera program [1]. The program Mathematica [2] is used to find a balance between the heat loads, the power vs. temperature performance characteristic of the cryocoolers and the calculated temperature distribution in the copper plates. Usually analyses iterate between the cryocooler performance characteristics and the intermediate cooling station temperature distribution FEA. A method has been developed to converge in one step.**

***Index Terms*—Cryocooler, Vector Fields Tempo, current leads.**

I. INTRODUCTION

THE INITIAL SIZING of the Copper Current Leads for the MICE Coupling Coil was reported in the studies by Michael Green [3] and Li Wang [4], which were based on the specifications [5, 6] for the CRYOMECH PT415 Cryocoolers and assumed that the first stages of all cryocoolers are at the same temperature (60 K).

FIG 1. HERE

The present study concentrates on the FE thermal analyses of the system shown in Fig. 1: intermediate cooling station integrating 3 cryocoolers on 3 copper plates connected by 2 pairs of copper joint straps, and 2 copper blocks with prongs for terminals for the optimized RT [7] and HTS current leads. The perimeter of the array of copper plates is bolted to the intermediate radiation shield.

Thermal FEA was performed using TEMPO, a thermal package of the Vector Fields Opera program. A separate program using Mathematica was written to find a balance between the heat loads, the power vs. temperature performance characteristic of the cryocoolers and the calculated temperature distribution in the copper plates. Here the performance of each cryocooler was taken into account individually, based on the calculated temperature of its first and second stages.

Manuscript received October 9, 2012. The present work was supported by the Office of Science, US-DOE under DOE contract DE-AC02-05CH11231

A. Radovinsky is with MIT-Plasma Science and Fusion Center, Cambridge, MA 02139 USA (e-mail: radovinsky@psfc.mit.edu).

A. Zhukovsky is with MIT-Plasma Science and Fusion Center, Cambridge, MA 02139 USA (e-mail: zhukovsky@psfc.mit.edu).

II. ANALYSES

A. Model

A FE model of the intermediate cooling station analyzed using TEMPO, a thermal package of the Vector Fields Opera program, is shown in Fig. 2. The parts are shown separated for better visualization.

FIG. 2 HERE

The Central (c) Copper Plate and two Side (s) Copper Plates are treated as separate parts. The below parameters related to these plates are marked by respective extensions, "_c" and "_s".

Boundary conditions Flux_cryo_c and Flux_cryo_s specify heat flux through the contact surface of the flange between the cryocooler and the Copper Plate. Boundary conditions Temp_cryo_c and Temp_cryo_s specify temperature at these interfaces. Boundary conditions Flux_shield_c and Flux_shield_s specify heat flux to the Copper Plates from the radiation shield. It is assumed to be distributed uniformly along the outer perimeter of the Copper Plate Assembly, so that Flux_shield_c = Flux_shield_s = Flux_shield. Finally, Flux_4k and Flux_300k specify the heat flux through surfaces of the Copper Block providing contact with the cold, HTS, and warm Copper Current Leads respectively. The details of defining these boundary conditions are explained below.

The thermal conductivities of all copper parts were defined as a function of temperature using the NIST data [8] for RRR=50.

In the model, the thickness of the insulator between the Copper Plate and the Copper Block is 0.3 mm, and its thermal conductivity is set to 0.886 W/m-K. This is equivalent to a 2-mil (0.0508 mm) layer of Kapton with thermal conductivity of 0.15 W/m-K [9], which is easily sufficient for the 1-kV voltage defined as a design target in [10].

Joule heating from the transport current, Ic, in the Copper Block is neglected. For Ic=210 A, joule losses are of the order of 10^{-3} W. Electrical heating due to the contact resistance at the connections of the Current Leads to the Copper Block is also neglected.

B. *Model A (MICECC-cu_plate-wa-2)*

The peculiarity of defining BCs for this model is related to the fact that the performance of each of the cryocoolers is a function of the temperature of its first station. We can assume that due to the symmetry, both Side cryocoolers are at the same temperature and provide the same cooling power. The Central cryocooler, connected to the Central Copper Plate and having a smaller contact perimeter with the radiation shield and carrying no direct heat loads from the current leads, provides less cooling power and has a lower working temperature. This results in a temperature drop between the higher temperature Side Copper Plates and the lower temperature Central Copper Plate. Consequently, this causes a heat flow through 2 pairs of copper Joint Straps. Defining a self consistent set of boundary conditions permitting a solution with temperature distribution and power balances compatible with the above requirements is a challenge.

Table I shows a full set of the BCs used in Model A. Column 1 contains the name of the BC. Column 2 shows temperatures corresponding to the respective BCs. These are temperatures of the first stations of the Central and Side Copper Plates. Columns 3 and 4 show the transferred heating power through and the area of the surface, on which this BC is specified. These surfaces are highlighted in yellow in the figures above. Column 5 contains the heat flux, which is the result of the division of the power by the area, through which it is transferred. Note that the table is divided into three parts: related to Both Plates, the Central Plate and to one of two Side Plates and the parts attached to them. Heat flux and the power are positive at interfaces with parts, which are at a higher temperature than the local temperature of the respective Copper Plate, and the other way around.

TABLE I HERE

Heat flux, Flux_shield_c = Flux_shield_s = Flux_shield, is calculated by dividing the total heat load at the first station from all sources, except for the Current Leads, by the area of the surface of the outer perimeter presumed to be in contact with the radiation shield. This power is conservatively set at 74 W as defined in [4] for a 100% contingency. Respective power loads on the Central and Side Copper Plates from the shield are P_shield_c=13.146 W and P_shield_s=30.427 W. Heat loads from the optimized RT [7] and HTS Current Leads can be set at P_300k = 10 W and P_4k = -0.15 W .

Heat capacities, Pc and Ps, of the cryocoolers attached to the Central and Side Plates as a function of the respective temperatures of their first stages, Tc and Ts, are defined by the formulae

$$Pc(Tc) = a_0 + a_1\, Tc + a_2\, Tc^2 + a_3\, Tc^3 + a_4\, Tc^4$$
$$Ps(Ts) = a_0 + a_1\, Ts + a_2\, Ts^2 + a_3\, Ts^3 + a_4\, Ts^4 \qquad (1)$$

Here a_0=-1489.5512, a_1=112.47614, a_2=-3.10904, a_3=0.03844, a_4=0.0001770150 are coefficients defined to match the diagram shown in Fig. 3 relating the capacity of the first stage of the cryocooler and the temperature of this stage (32K<T<70K) for the second stage held at 4.2 K.

FIG. 3 HERE

Power balances for the Central and the Side Copper Plate subassemblies can be expressed analytically as

$$- Pc(Tc) + P\_shield\_c + 2*P\_straps = 0$$
$$- Ps(Ts) + P\_shield\_s + P\_300k + P\_4k - P\_straps = 0 \qquad (2)$$

Here all components are either constant values or functions of Tc and Ts. The only undefined function is P_straps. This is the power shared between the Copper Plates through a pair of Copper Straps shown in Fig. 2. From simulations of several subsidiary models, it was concluded that it would be valid to make the following assumptions:

- Temperature drop across the copper plate between the first station of the cryocooler and the points of attachment of the Straps is small compared to the minimum temperature drops between the Central and the Side Copper Plates;
- Heating power through the Straps is proportional to the temperature drop between the points of contact with the Copper Plates at the ends of the Straps.

Consequently we can assume that

$$P\_straps = dPdT*(Ts - Tc) \qquad (3)$$

where dPdT is a coefficient, which was calculated using a subsidiary FE model. Analyses showed that for dT= Ts - Tc =5 K, the power integral through the pair of Straps is P_straps=56 W. The coefficient in (3) is

$$dPdT= P\_straps/(Ts - Tc) = 56\ W/5\ K = 11.2\ W/K \qquad (4)$$

Solving the nonlinear system of equations (1), (2), (3) and (4) using Mathematica, we can calculate a combination of values of the temperature and cooling power of cryocoolers, (Tc, Pc) and (Ts, Ps), which is expected to provide a power balance between the plate subassemblies with the account of heat transfer through the straps.

For the baseline Model A, these values were calculated (underscored in Table I).

The expected power depositions to the Central and Side Copper Plates through the Straps are shown in Table I in italics. They are calculated from the respective balances (2). They are not specified in the model; instead they can be used for verifying the quality of the solution by the degree of its convergence to a proper power balance based on the cryocooler performance vs. temperature diagram.

In this particular case, the calculated power transferred through a pair of Straps is 7.377 W, which is close to the expected |P_straps| = 7.982 W in Table I.

C. *Model B (MICECC-cu_plate-wo-clips-1)*

Model B was created and analyzed to assess the value of having Straps connecting the Copper Plates.

This model is the same as above with the following exceptions. First, there are no Straps connecting the Copper Plates. Second, boundary conditions in the part specifying the cryocooler first station temperature and cooling power are calculated using the same equations (1)-(2), only in this case P_straps=dPdT=0 and these equations are solved independently. The full set of boundary conditions for this model is shown in Table II.

TABLE II HERE

Note that in this case, the Central cryocooler delivers 3 times less power than each of the Side cryocoolers. It's temperature is almost 6 K lower.

III. Conclusions

The following conclusions can be made from analyzing results shown in Tables I and II:

1. The results of thermal analyses of Model A representing the baseline design of the Intermediate Cooling Station showed that this design is acceptable. Due to the abundance of cooling power at the first stations of the cryocoolers, their temperatures are close to 37 K, and the cooling power is evenly shared with 29 W in the Central cryocooler and 32 W in the Side cryocoolers.

2. 1.5-cm thick Copper Plates provide sufficient thermal conductivity to limit temperature drops between the cryocooler and any point of the Copper Plate to less than 1 K.

3. With a 2-mil Kapton insulator between the Copper Plate and the Copper Block, the warmest point of the model, the Copper Current Lead terminal of the Copper Block, is just 2 K warmer than the first station of the cryocooler attached to the Side Copper Plate. The temperature drop across the insulator is a fraction of 1 K.

4. Power sharing between the Central and two Side Copper Plates is essential for redistributing the cooling power of the cryocoolers. Without the Copper Straps, the Central cryocooler has only 1/3 of the load of each of the Side cryocoolers, and its working temperature is almost 6 K lower.

5. The purpose of the Copper Straps is to allow independent flotation of the Copper Plates to avoid overstressing the structure of the cryocolers between the RT and the first station flanges due to differential thermal contraction. Structural analyses can show the necessity for flexibility of the straps. The spec for choosing these flexible thermal links is that the thermal resistance of a connection between any of the Side Plates to the Central Plate at 40 K has to be no less than dPdT=11.2 W/K as defined in this study.

Acknowledgment

The present work was supported by the Office of Science, US-DOE under DOE contract DE-AC02-05CH11231

References

[1] Vector Fields Opera Software, www.cobham.com/technicalservices
[2] Mathematica, computer program, http://www.wolframresearch.com
[3] Michael A. Green, "Results from the Cooler and Lead Tests," MICE Note 291, Lawrence Berkeley National Laboratory, 20 June 2010
[4] WANG, Li, "Calculations and FEA simulations for MICE/ Muool Coupling Magnet Cryostat Design," Review at SINAP/Shanghai, 12-09-2010
[5] http://www.cryomech.com/PT415.php
[6] Y. S. Choi, T. A. Painter, D. L. Kim, et al, "Helium-Liquefaction by Cryocooler for High-Field Magnets Cooling, " Proceedings of the International Cryocooler Conference (2006)
[7] Richard McFee, " Optimum Input Leads for Cryogenic Aparatus," The review of Scientific Instruments, February, 1959, V. 30, No. 2, p. 98.
[8] http://cryogenics.nist.gov/MPropsMAY/OFHC%20Copper/OFHC_Copper_rev1.htm
[9] D.J. Bendorf, T.J. Powers, S.H. Moseley, "Thermal conductivity of Kapton tape", Cryogenics 39 (1999) pp. 93-95.
[10] B.A. Smith, S. Prestemon, H. Pan, " Design and analysis of the quench protection system for the MICE coupling coils" submitted for publication.

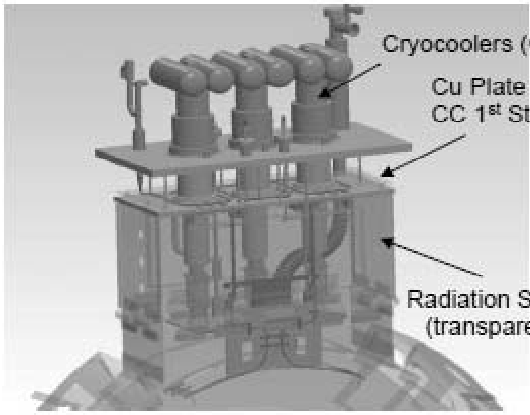

Fig. 1. Intermediate Cooling Station

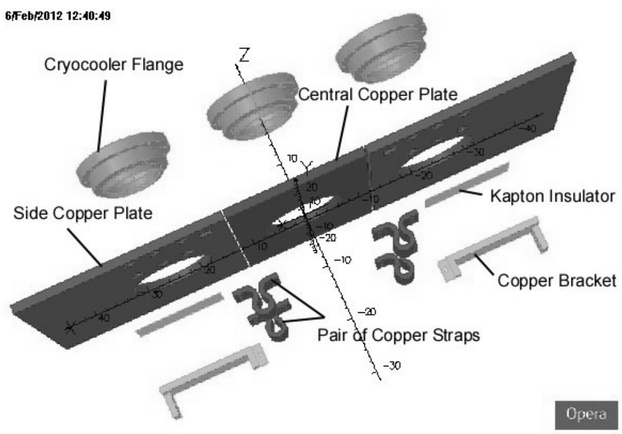

Fig. 2. FEM Parts Diagram

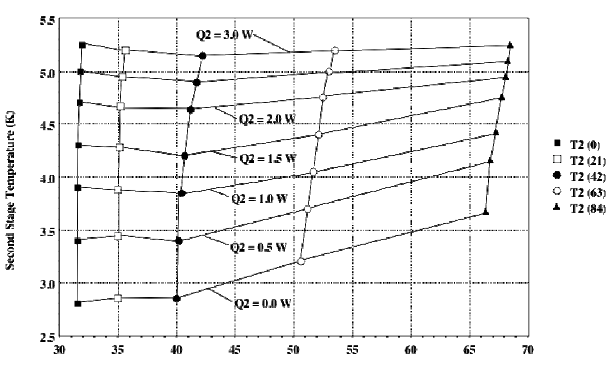

Fig. 3. Operating temperature diagram for the first-stage temperature T1 and the second-stage temperature T2 of a PT415 pulse tube cooler as a function of the first-stage heat load Q1 and the second stage heat load Q2. (Data taken by Florida State University [6].)

TABLE I

Boundary Conditions	(T)emp	(P)ower	(A)rea	(F)lux=P/A
	K	W	cm^2	W/cm^2
1	2	3	4	5
Both Plates				
Flux_shield		74.000	418.80	0.177
Central Plate				
Flux_shield_c		13.146	74.40	0.177
Flux_cryo_c		-29.110	67.10	-0.434
Temp_cryo_c	36.554			
*- 2*P_straps*		*15.964*		
Side Plate				
Flux_shield_s		30.427	172.20	0.177
Flux_cryo_s		-32.295	67.10	-0.481
Temp_cryo_s	37.267			
Flux_300k		10.000	4.76	2.101
Flux_4k		-0.150	13.30	-0.011
P_straps		*-7.982*		

TABLE II

Boundary Conditions	(T)emp	(P)ower	(A)rea	(F)lux=P/A
	K	W	cm^2	W/cm^2
1	2	3	4	5
Both Plates				
Flux_shield		74.000	418.80	0.177
Central Plate				
Flux_shield_c		13.146	74.40	0.177
Flux_cryo_c		-13.146	67.10	-0.434
Temp_cryo_c	33.739			
*- 2*P_straps*		*0.000*		
Side Plate				
Flux_shield_s		30.427	172.20	0.177
Flux_cryo_s		-40.277	67.10	-0.481
Temp_cryo_s	39.427			
Flux_300k		10.000	4.76	2.101
Flux_4k		-0.150	13.30	-0.011
P_straps		*0.000*		