Cryogenic Heat Sink for Helium Gas Cooled Superconducting Power Devices

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Abstract: Heat sinks for cryogenic applications using helium gas as the coolant are not readily available. They require to be designed specifically for the intended application in a cable termination for a superconducting power cable. A finite element model was developed to study the feasibility and optimize the design. The finite element computing package COMSOL Multiphysics allowed to couple fluid flow and heat transfer as needed. An experiment was designed to validate the results obtained by numerical simulation. It allowed to measure gas temperature increase and heat sink temperature as a function of gas pressure, coolant inlet conditions and heater power. The results of the finite element model correspond reasonably well with the experiment. The model will be useful to design larger heat sinks for application in actual power system apparatus.

Keywords: Heat sink, Power cable, Superconductor, Helium, Optimization.

1. Introduction

Power cables have terminations on each end to guarantee dielectric integrity: They interconnect the power cable with its high electric field to air-insulated components with lower electric fields changing ambient conditions. In case of a superconducting power cable, the terminations additionally need to link the cryogenic environment in the cable with the ambient temperature environment of the non-superconducting elements of the power system, such as copper cables, power transformers, circuit breakers, instrumentation transformers, or disconnect switches. The higher temperatures of these components cause substantial heat influx into the terminations and consequently into the superconducting cable. It is utmost important to minimize the heat influx to maintain the operating temperature of the superconducting cable well below critical levels as well as to minimize the installed cryogenic capacity and operating costs of the superconducting cable system.

The common method of cooling for high temperature superconducting (HTS) power devices is to use liquid nitrogen in the temperature range of 68−77 K. However, the cable type investigated in this study uses cryogenic helium gas at elevated pressure as the coolant. The choice of coolant is driven by the intended application for shipboard power systems, where the use of liquid cryogens poses potential unacceptable asphyxiation hazards as well as high pressure hazards associated with phase change [1]. However, gaseous helium makes the cable more sensitive to heat influx since the heat capacity of helium gas is significantly lower to that of liquid nitrogen. A heat sink is required to intercept the heat leak from the room temperature components to the superconducting cable (Figure 1). COMSOL Multiphysics was used to study the feasibility as well as an optimization tool for such a copper heat sink.

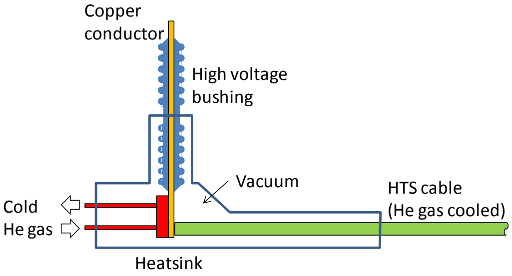

Figure 1. A schematic of the superconducting cable termination with heat sink (red), cable (green), and copper conductor (yellow)

The heat sink designed and modeled in this study is made of copper and features 18 fins of 10 cm length as shown in Figure 2 (patents pending [3][4]). It is integrated in a cylindrical copper tube, flattened on the bottom side. The flat surface allows for known and variable thermal load to the heat sink. Cryogenic helium gas is injected at high pressure by an external helium circulation system [2]. The input temperature and pressure at the heat sink can be adjusted depending on cooling requirements. The assembled heat sink was wrapped in aluminized Mylar foil and enclosed in a vacuum chamber to reduce the heat transfer from the ambient. This particular heat sink was designed and fabricated specifically for the model validation. It is a miniature version of the heat sink needed for actual superconducting power device applications.

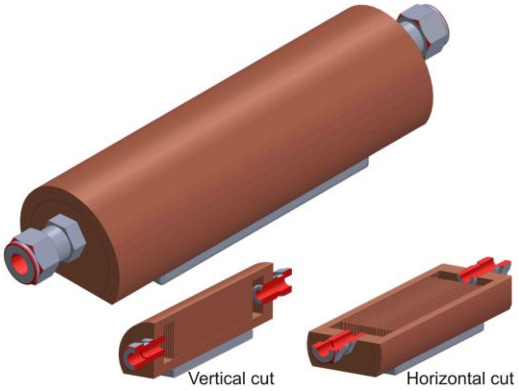

Figure 2. Design of the heat sink (total view) and cut views to show the internal fin structure (vertical and horizontal cut)

2. Finite Element Model

The heat sink in Figure 2 is only a prototype to validate the computational models. Once these computational models are properly validated, they will be used to optimize the geometry of the actual product used in future applications. The models will also help in calculating the required cooling power for large cable systems with several terminations and therefore several heat sinks.

In the course of model development, two versions are of special interest as discussed in detail below. They are both implemented in *COMSOL Multiphysics 4.3* using the *Heat Transfer Module*.

2.1 Two-Dimensional Heat Transfer

The first finite element model is designed to determine the ideal number of fins for a given overall width of the base plate of the heat sink. A two dimensional steady-state model is implemented for this purpose. The focus is solely on heat transfer, i.e. excludes fluid flow. *Heat Transfer in Soilds (ht)* physics module in *COMSOL Multiphysics 4.3* is used for the same. The geometry is parameterized to easily allow sweeping over the number of fins. In this case both geometric and thermal symmetry is assumed.

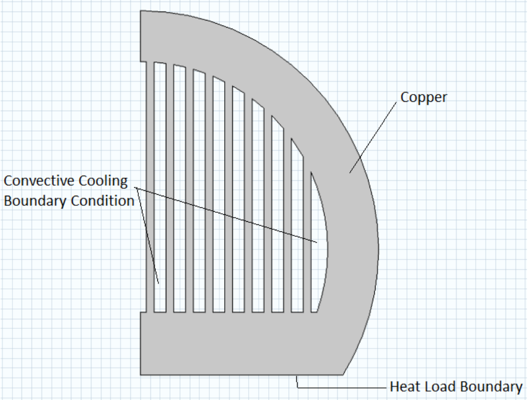

Figure 3. 2-Dimensional model of the heat sink

The 2-D model is as shown in Figure 3. The heat transfer in the solid block of copper is governed by conduction equation as represented by COMSOL as

$$\rho c_p u \cdot \nabla T = \nabla \cdot (k \nabla T) + Q$$

The properties of copper viz, k, thermal conductivity, c_P, specific heat at constant pressure, ρ, density are default as defined by COMSOL for copper material.

The initial temperature in the entire domain was considered to be 50 K with a total heat input of 50 W at the base of the 2D model. The helium flow is modeled to be in the laminar region with convective cooling boundary condition on the fin walls. An effective heat transfer coefficient value of $h = 90.25\ \mathrm{W/m^2K}$ for the convective boundary condition is used for the 9 fin model. Separate values of h are calculated based the Dittus-Boelter correlation. The pressure drop is calculated separately using the Moody Diagram and laminar regime correlations. The governing equation for convective cooling is represented in COMSOL as follows:

$$-n \cdot (-k \nabla T) = h \cdot (T_{ext} - T) + q_0$$

The heat load is applied at the flat bottom face (appearing as a line), as a boundary condition to represent the actual heater surface with a total heat input of 50 W.

The mesh size is chosen as “normal” with the default values as available in the general physics category. The normal mesh with 2986 elements is sufficient to satisfy mesh independence. *Stationary Linear Solver* produced the results as shown below in Figure 4.

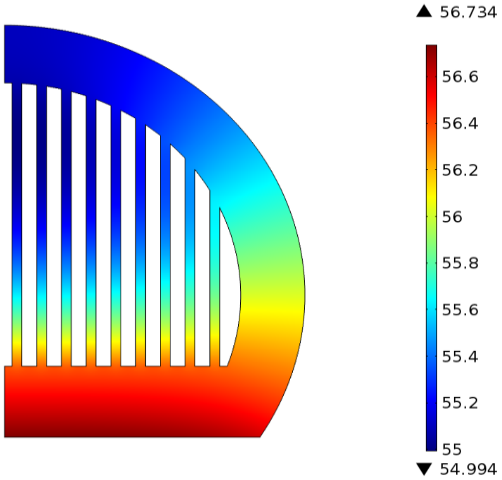

Figure 4. Surface temperature of the heat sink (in Kelvin)

The purpose of the 2D computation was to find the number of fins required for optimum performance of the heat sink, i.e., a best tradeoff between temperature gradient and pressure drop across the heat sink. Figures 5 and 6 show that for that 9 fin heat sink model results in a proper balance between the pressure drop and temperature gradient. This result forms the building block for carrying out further detailed 3D studies.

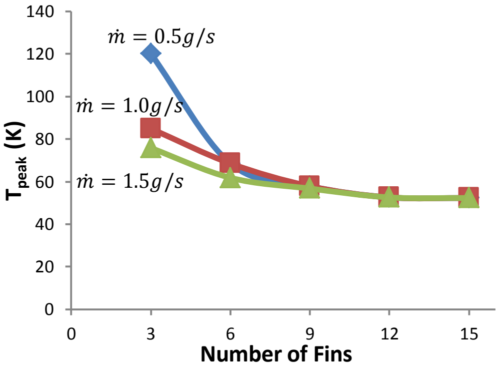

Figure 5. Peak temperature variation with mass flow rate

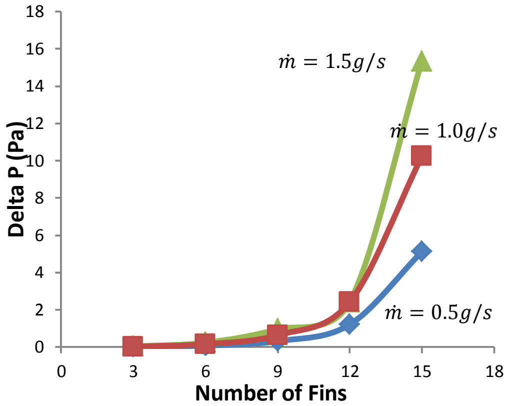

Figure 6. Pressure drop behavior as a function of mass flow rate across the channel.

2.2 Three-Dimensional Fluid Flow

The purpose of the fluid flow model was to optimize the spacing between fins. In order to maximize heat transfer to the fluid, the flow should be evenly distributed between the fins. Of equal importance is the total pressure drop across the heat sink. Cryogenic circulation systems have typically limited pressure drop capabilities.

The fluid flow could not easily be reduced to two dimensions since the entrance and exit chambers substantially impact the flow pattern. Therefore a three dimensional model was developed. The model has been developed using the *Conjugate Heat Transfer* physics in COMSOL Multiphysics 4.3 to simulate the stationary, three dimensional fluid flow and heat transfer. The fluid velocity field was low enough to be assumed as laminar flow. Again, the geometry, thermal field and fluid flow are assumed to be symmetric to the vertical longitudinal plane for faster computational convergence.

The properties and equations for the solid copper block are the same as used for the 2D model. However an additional helium fluid domain is added here. The governing equations, represented in COMSOL, are as follows:

$$\rho(u \cdot \nabla)u = \nabla \cdot \left[-pl + \mu(\nabla u + (\nabla u)^T) - \frac{2}{3}\mu(\nabla \cdot u)l\right] + F$$

$$\nabla \cdot (\rho u) = 0$$

$$\rho c_p u \cdot \nabla T = \nabla \cdot (\mathrm{k}\nabla \mathrm{T}) + Q + Q_{vh} + W_p$$

The fluid properties (density, ρ, kinematic viscosity, μ, thermal conductivity, k, specific heat, c_p) are evaluated at the average working temperature. Laminar flow conditions are assumed consistent with the experimental mass flow rates. The inlet velocity profile is assumed to be parabolic. The fluid enters at a certain pressure and temperature which are set as input boundary conditions for the problem. A symmetric boundary condition is applied to ensure geometric and thermal symmetry.

The meshing is carried out with an aim to keep the computational time as short as possible and yet not affect the results thus obtained. The solid is meshed by a "normal" sized mesh whereas the fluid and its interface with the solid are meshed with a "finer" sized mesh. This amounts to a total of 1.54 million elements taking 156 minutes on a computer with eight CPU cores (2× Intel Xeon X5570) to compute the steady state results. The results are computed using the stationary solvers, which incorporate a GMRES solver and a non-linear solver at default settings. GMRES required 240 iterations and the non-linear solver 45 iterations to arrive at steady state results as shown in Figure 7.

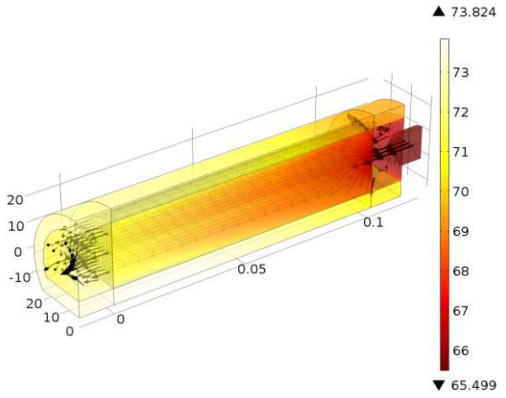

Figure 7. Surface temperature of the heat sink along with the velocity field of the fluid flow (in Kelvin)

4. Experimental Validation

Experiments have been set up to validate the results obtained by the simulation. The heat sink consists of four parts: The base block with fins, two end plates, and the surrounding enclosure (Figure 8). All parts except for the cuts between the fins were machined mechanically. The cuts were machined by electrical discharge machining (EDM). The four parts were joined through silver brazing for maximum conductivity and excellent structural strength. The supply tubes were soldered to the end plates using tin-lead solder. A heater was attached to the bottom plate. Two temperature sensors were attached to the side walls of the heat sink.

The heat sink was then wrapped in aluminized Mylar (multi-layer insulation, MLI) and installed in the vacuum chamber. Two additional temperature sensors were attached to the supply and exit tubes to measure the inlet and outlet fluid temperatures. An adjustable DC voltage source was used to control the heat influx to the heat sink. The helium circulation system allowed adjusting the pressure and temperature of the helium inflow. A differential pressure gauge was used to measure the pressure drop across the heat sink.

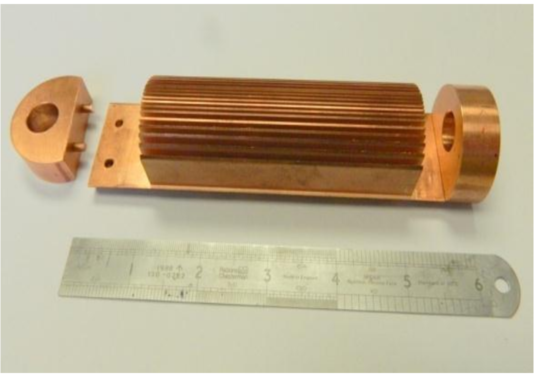

Figure 8. Parts of the heat sink before brazing them together. The total length is 152 mm.

Two different cases with 50 W and 100 W heat input were studied at certain helium pressure and mass flow rate conditions as shown in Table 1. For the 50 W case, the input helium conditions are 857 kPa and 58.6 K whereas for 100 W heat input these values are 973 kPa and 65.5 K respectively. These values are used as inputs to simulate the results for temperature gradient and pressure drop across the heat sink. The resulting outlet temperature and pressure drop correspond reasonably well with experimental values. However, the calculated temperature increase of the maximum heat sink temperature is considerably lower than the measured value from the experiment. The reason for the mismatch is currently being investigated.

Table 1: Comparison of simulation results with measurements

Parameter	50 W		100 W	
	Model	Exp.	Model	Exp.
Temperature inlet [K]	58.6	58.6	65.5	65.5
Temperature increase [K]	4.15	4.7	6.45	7.3
Temp. heat sink [K]	63.0	77.3	73.8	84.0
Pressure drop [Pa]	284	294	313	297

5. Conclusions

As can be seen in the Figure 11, the simulations results for helium temperature difference and pressure drop across the heat sink are a close match with the experimental values under the same input conditions. Thus the copper heat sink device can be efficiently and effectively modeled under the constraints of maximum allowable pressure drop and/or space restrictions. Thus this model is a useful tool to optimize a heat sink for superconducting power cables and other allied devices. However, the results for the maximum temperature of the copper block do not match with the experimental results. It is not clear if the mismatch of the heat sink temperature is caused by measurement inaccuracies or by an error in the finite element model.

Thus the future work includes preparing a more robust COMSOL *Multiphysics* model to include density variations of helium gas with temperature. This can be used to optimize for various geometries and fins to have more effective and efficient heat sink devices for superconducting applications. A turbulent model for any scale of input conditions would be ideal to provide a general heat sink optimization tool for a variety of cryogenic applications.

6. Acknowledgement

This work has been benefited from funding from the United States Office of Naval Research (ONR) and the Naval Engineering Education Center (NEEC).

7. References

1. Kephart, J.T., Fitzpatrick, B.K., Ferrara, P., Pyryt, M., Pienkos, J., Golda, E.M., High Temperature Superconducting Degaussing from Feasibility Study to Fleet Adoption, *IEEE Trans. on Applied Superconductivity*, **21**, 2229–2232 (2011).
2. Sastry Pamidi, Chul Han Kim, Jae-Ho Kim, Danny Crook, Steinar Dale, Cryogenic helium gas circulation system for advanced characterization of superconducting cables and other devices, *Cryogenics*, **52**, 315–320 (2012).
3. L. Graber, H. Rodrigo, D.G. Crook, S. Pamidi, S.J. Dale, B. Trociewitz, Cable Termination for High Voltage Power Cables Cooled by a Gaseous Cryogen, *US Patent*, pending (2012)
4. D. G. Crook, L. Graber, S. Pamidi, Cryogenic Heat Sink for Helium Gas Cooled Superconducting Power Devices, *US Patent*, pending (2012)