Thermal Analysis of the TPX TF Coil Case for Eddy Current and Neutron Heating

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Abstract—A finite element, thermal analysis of the Tokamak Physics eXperiment's (TPX) toroidal field (TF) coil case is presented. The analysis models the 316LN coil case as a 3-D shell with imposed thermal loads dominated by neutron and eddy current heating. Heat sinks which simulate the flow of supercritical helium in the coil case cooling system and adjacent conductor conduits are used to extract the steady-state heat load. The model is used to estimate the heat leak rate into the winding pack as input for heat removal and conductor temperature margin calculations. The proposed cooling scheme flows 5 K helium at 5 atmospheres, to the TF coil winding packs. The effluent is directed into the case cooling channels. Results indicate that the case cooling system and ground wrap insulation are effective means of thermally isolating the superconductor from the heat deposited in the coil case; 92 % of the 8.07 kW deposited in the coil cases by eddy currents and neutrons gets extracted by the helium flowing in the case cooling channels while only 0.65 kW are transmitted into the adjacent conductors of the winding packs.

INTRODUCTION

Current fluctuations in the vertical stability plasma control coils induce eddy current heating in the TPX TF coil cold structure. Joule heating in the case averages 1.4 kW during the 1000 second plasma flattop [1] and can, therefore, be considered a steady-state thermal load. An additional heat load comes from D-D fueled plasmas. With a design fluence of 7.5 x 10^{16} neutrons/s, analysis indicates that this nuclear load will deposit 6.67 kW of heat into the magnet system support structure [2], [3]. These two major heat loads total just over 8 kW deposited into the TF coil cold structure.

The TF coil case cooling design philosophy has been to intercept most of this Joule and neutron heat load with supercritical helium flowing through channels in the case wall. However, some amount of heating will conduct through the coil ground wrap insulation and into the helium-cooled conductors. This heat load has the adverse effect of a direct impact on the stability and safety margins of the superconductor.

This paper describes an analysis which estimates the steady-state heat transfer rate into the TF coil winding pack and case cooling channels as a result of Joule heating from eddy currents and nuclear heating from D-D plasmas. The analysis also evaluates the proposed cooling philosophy in which the winding pack effluent helium is routed directly into the TF coil case cooling channels.

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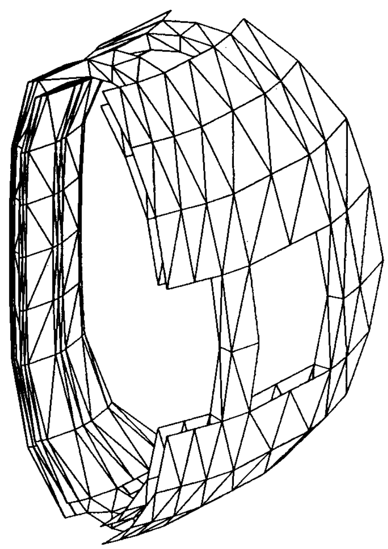

Fig. 1. Isometric view of 3-D thermal model, two TF coil subassembly.

FINITE ELEMENT MODEL

The 3-D, thermal, finite element ANSYS [4] model as shown in Fig. 1 was first presented in [5]. Thermal shell elements are used to simulate the TF coil case and intercoil support structure. Thermal bricks are attached to the insides of the coil case to simulate the conduction path to the winding pack helium, such as across the ground wrap, turn insulation and Incoloy 908 conduit wall. Convection surface elements are included to simulate the convection heat transfer into the helium which flows in the case cooling channels and conductor conduits.

The analysis simulates the so-called *bolted-welded* four-coil TF module with a symmetric, two-coil model. The name refers to the joint type on each side of the assembly, used to connect adjacent modules to form the 16 coil TF magnet system. In Fig. 1, the left side of the outboard leg has the geometric characteristics of a bolted joint; flanges are located above and below a large, horizontal port. The right side of the figure shows a welded joint, which spans the full height of the outboard leg, with no breaks to accommodate a horizontal port. These are also planes of thermal symmetry.

The TF coil case cooling system uses channels which are integral to the case, as shown in the drawings of [6]. A series of nine, 0.00635 m by 0.01905 m (1/4" by 3/4") channels are machined into the entire inner, plasma-facing steel band and a series of ten, 0.003175 m by 0.01905 m (1/8" by 3/4") cooling channels are machined into the case side-walls, except in the inboard leg, or wedged region. The channels are covered by a thin plate, which provides a closed cooling circuit for the helium.

The thermal resistance between the case wall and the helium in the winding pack is composed of the contact resistance between the case and the winding pack, the ground and turn wrap insulations, a conduit wall, and a convection film coefficient. In the analysis presented here, the contact resistance is conservatively ignored, and an equivalent heat path is modeled by a layer of G-10-like insulation. A convection surface is located inside the layer of insulation to simulate the heat transfer between the conduit wall and the helium which flows inside the conduit.

Thermal analysis of the TF conductor indicates that the helium enters the winding pack at 5 K, rises to a peak value of about 6 K and exits at 5.7 K [7]. An equivalent heat transfer coefficient is calculated, with convection to an average helium temperature of 5.8 K.

Convection surfaces are also placed directly on the case walls to simulate the helium flowing in the case cooling channels. In this case, establishing the average helium temperature requires an iterative approach, since the amount of heat convected into the case-cooling helium is a function of its temperature. However, the inlet conditions are known: mass flow rate, 0.45 kg/s, temperature, 5.7 K, and pressure, 3.0 atmospheres. As in the winding pack, it is assumed that the case is cooled by constant temperature helium.

A. Equivalent Thermal Conductivity

There are two conduction heat transfer paths between the TF coil case and the winding pack. One path is radial, from the inner and outer case bands to the coil. The other path is lateral, from the case side-walls to the coil. Each path contains a mixture of insulation and steel. The thicknesses and thermal conductivities of each constituent in the path are summarized in Table I. An equivalent thermal conductivity (k_{eq}) is calculated for each path, based on the following expression, and included in Table I.

$$k_{eq} = (t_{ins} + t_{908})/\{(t_{ins} / k_{ins}) + (t_{908} / k_{908})\}$$

B. Convection Film Coefficient

The analysis postulates that the heat generated in the TF coil case wall is carried away by constant temperature helium flowing in the case cooling channels and in the conductor conduit. Convection heat transfer coefficients (h) are calculated for these surfaces based on the equations given in [8] and shown below.

$$h = kN/d_h$$

The Nusselt number (N) and the hydraulic diameter (d_h) are given by,

$$N = 0.26\, Re^{0.8}\, Pr^{0.4}\, (T / T_w)^{0.716}$$

$$d_h = 4\, A / P_w$$

and can be applied to flows with Reynolds numbers (Re) greater than 10,000. The Reynolds and Prandtl (Pr) numbers are defined as,

$$Re = \rho\, V\, d_h / \mu$$

$$Pr = C_p \mu/k$$

where A is the cross-sectional flow area, P_w is the wetted perimeter of the flow area, V is the flow velocity, T is the bulk fluid temperature and T_w is the wall temperature. The specific heat C_p, thermal conductivity k, viscosity μ, and density ρ, are fluid properties, which are a function of pressure and temperature. Upon substitution, the equation for the film coefficient reduces to:

$$h = [k(H+W)/(2HW)] \times [0.026(2MFR/\mu(H+W))^{0.8} (Pr)^{0.4} (T/T_W)^{0.716}]$$

where H and W are the height and width of an individual flow channel, and MFR is the corresponding mass flow rate.

Values for the film coefficient are calculated for the flow in the conduit and case wall cooling channels. In the steady-state condition, the temperature difference across the fluid film is small, and the $(T/T_w)^{0.716}$ term can be neglected. This is confirmed by the analysis, which indicates a 12% effect from this term, based on a fluid T of 5 K and a localized T_w of 6 K. Results *Section B,* discusses the sensitivity of the heat distribution to uncertainties in the film coefficient values.

1) Helium Flow in the Conductor: The TF system design description [9] indicates that 0.450 kg/s of 5 atmosphere, 5 K helium is available to cool the conductor. The flow is split equally among the 16 coils, and the six double pancakes per coil. Thus, helium flows at 0.00469 kg/s through each conduit. Helium fluid properties (μ and Pr) are provided by the curves of [10].

The flow rate, channel dimensions, and helium fluid properties are used in the equation shown above to determine the film coefficient for a variety of pressures. The results indicates that the film coefficient varies little over the expected 3 to 5 atmosphere pressure range. Therefore, an average value of 210 W/m²/K is used to evaluate the heat transfer to an average helium temperature of 5.8 K flowing in the conductor.

TABLE I
CONSTITUENT AND EQUIVALENT CONDUCTION PROPERTIES (5 K) AND DIMENSIONS

Parameter	Conduction Path from Side-Walls to Winding Pack	Conduction Path from Inner and Outer Band to Winding Pack
Insulation thk [m]	0.0142	0.020
Insulation K [W/m/K]	0.06	0.06
Conduit thk [m]	0.00241	0.00241
Conduit K [W/m/K]	0.28	0.28
Equivalent thk [m]	0.0166	0.0224
Equivalent K [W/m/K]	0.068	0.066

TABLE II
CONVECTION FILM COEFFICIENTS USED IN FE MODEL [W/m²/K]

Temp. [K]	h, Case Channel Helium		h, Winding Pack Helium	
	Side-wall	Inner Band	Side-wall	Radial Surf.
5	260	260	170	150

However, since the convection areas used in the model are larger than the actual areas exposed to flowing helium, this average film coefficient must be scaled down proportionally. Dividing the actual side-wall convection surface width by the modeled convection surface width gives a scale factor of 0.83. Similarly, dividing the actual radial convection surface width by the modeled convection surface width gives a scale factor 0.71. The scaled film coefficient values used in the model are listed in Table II.

2) Helium Flow in the Case Cooling Channels: The analysis assumes that the entire 0.45 kg/s helium flow is available to pass through the cooling channels in the 16 TF coil case walls. Here, the 0.028 kg/s helium flow per coil case is assumed to split to maintain the same velocity in all channels. This results in 0.001 kg/s in each of the 10 sidewall channels, and 0.002 kg/s in each of the nine inner band channels.

Calculating the film coefficients for flow through the side-wall and inner band channels yields average film coefficients of 330 and 300 W/m²/K, respectively.

As described above, the difference between the modeled and the actual convection surface areas requires adjusting these film coefficient values. In this case, the scale factors are 0.78 for the side-wall values, and 0.88 for the plasma-facing inner band values. These scaled film coefficient values are also summarized in Table II.

C. Thermal-Hydraulic Calculation of Case Cooling

The temperature rise and pressure drop of the helium flowing in the case cooling channels is calculated with the aid of HE-SS [10]. The calculation includes the effects of friction, but there is some uncertainty in the friction factor. A range of values is applied to bracket the results. Input for the analysis is shown in Table III.

D. Assumptions

1. Inlet flow velocity is the same for the 0.00635 m by 0.01905 m and the 0.003175 m by 0.01905 m channels.

2. Convection heat transfer is to an average bulk helium temperature along the entire flow path in the winding pack and TF coil case.

RESULTS

A. Heat into Winging Pack and Case Cooling Circuits

The steady-state thermal analysis is run with the eddy current and nuclear heat loads described earlier, equivalent conduction heat paths to the winding pack as shown in Table I, and convection heat transfer coefficients as shown in Table II. The rates at which heat is absorbed by the TF winding pack and cooling channels are noted. A heat balance calculation is performed to confirm the assumed average TF coil case helium temperature. A modest error in the initial temperature guess produces converged results in one or two iterations.

TABLE III
INPUT VARIABLES USED IN THERMAL HYDRAULIC ANALYSIS OF CASE COOLING CHANNELS

Input Parameter	Input Value
Channel Length	11 m
Channel Area As-Designed:	(9) 0.0191 m x 0.00635 m (10) 0.0191 m x 0.00318 m
As-Modeled:	(19) 0.0191 m x 0.00467 m
Wetted Perimeter	0.0475 m per channel
Helium Flow	0.450 kg/s to16 cases, each with 19 channels: 0.00148 kg/s
Inlet Temperature	5.7 K
Inlet Press.	3.0 atmospheres
Applied Heat Load	7.42 kW over 16 coils, 19 channels, each 11 m long yields 2.22 W /m
Friction Factor	varied from 1 to 3.75

The analysis indicates that 7.42 kW of the 8.07 kW total is picked up by the helium which flows in the case cooling channels. Entering at 5.7 K and 3.0 atmospheres, the helium exit temperature and pressure is 7.1 K and 2.996 atmospheres, respectively. The range of assumed friction factor has little effect on these values.

Contour plots of the heat flux across the convection surface elements indicate where the heat loads are the highest, and how effective each heat sink is at removing heat from the coil case. Fig. 2 shows the heat flux into the conductors which border the TF winding pack. Recall that the heat, originating in the case, must pass across ground wrap insulation before it can be picked up by the helium in the conductor. The plot shows that the only significant heat load occurs around the equatorial plane of the inboard leg, with a magnitude of about 25 W/m². Although small in magnitude, the heat flux here is exacerbated by the lack of cooling channels in the sidewalls.

Fig. 3 shows a plot of the heat flux into the winding pack. The heat flux is a maximum in the region of the outboard leg and horizontal port, where the heat load from the case is greatest and where the winding pack is surrounded by cooling flow on three of four sides. Here the heat flux peaks at about 300 W/m², substantially higher than the heat flux entering the winding pack.

B. Sensitivity Study

To support these results, a sensitivity study has been conducted to investigate the effects of uncertainty in the heat transfer coefficient values. The study postulates a factor of two variation on the values calculated above, each conservatively skewed to maximize the amount of heat conducted into the winding pack. The heat transfer coefficient values of the helium flowing inside the conductor are increased by a factor of two, while the h values of the helium flowing in the case wall cooling channels are decreased by a

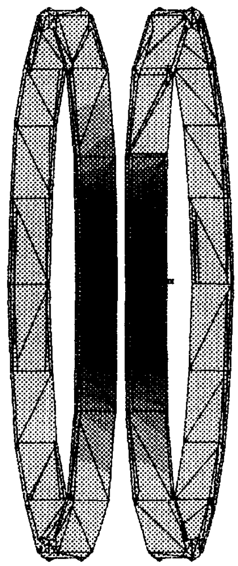

Fig. 2. Heat flux into the winding pack. Darkest region shows the location of the peak heat flux of 25 W/m^2.

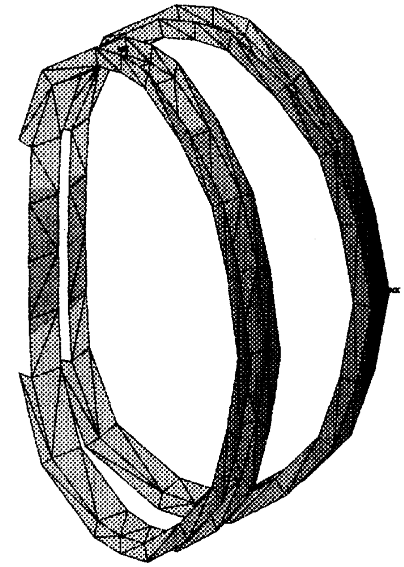

Fig. 3. Heat Flux into Case Cooling Channels. Darkest region represents a heat flux of about 300 W/m^2.

factor of two. The result is a small increase in the power absorbed by the winding pack, up about 0.1 kW.

The sensitivity study is extended to investigate the effects of uncertainties in the equivalent thermal conductivity. Decreasing the values calculated above by a factor of two, results in a decrease in the power absorbed by the winding pack, down about 0.1 kW. Increasing the equivalent thermal conductivity by a factor of two, results in an increase in the power absorbed by the winding pack, up about 0.1 kW.

It is interesting to see that fairly significant variations to these thermal constants has a rather minor impact on the total amount of heat which gets conducted into the winding pack. This is because the thermal resistance across the ground wrap is large compared to the heat path into the case cooling channels.

CONCLUSIONS

The conservative, 3-D, thermal, finite element analysis of the TF coil cold structure indicates that 0.65 kW conducts into the TF coil winding pack as a result of its thermal contact with the case. This is 8% of the 8.07 kW deposited in the TF case structure from nuclear and eddy current sources. About two-thirds of the heat (0.43 kW) which conducts from the case into the winding pack comes in from the case bands, while the remaining one-third (0.22 kW) conducts in to the winding pack from the case side walls. The other 7.42 kW is intercepted by the helium which flows in the case cooling channels.

In addition, a thermal-hydraulic analysis of the TF case cooling circuit using HE-SS indicates that 5.7 K, 3.00 atmosphere winding pack helium effluent will exit the TF case at 7.1 K, 2.996 atmosphere. This implies that the proposed series cooling of the winding pack and coil case can be achieved with minimal impact to the system pumping requirements. However, there may be other considerations such as flow control and instrumentation which need to be evaluated.

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