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Thermal Analysis and Testing for DIII–D Ohmic Heating Coil Repair*

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Abstract — The DIII–D ohmic heating (OH) coil solenoid consists of two parallel windings of 48 turns each cooled by water. Each winding is made up of four parallel conductors. Desired thermal capacity of the coil is 20 MJ at a repetition rate of 10 min. One of the conductors started leaking water in July 1995. Since then, the coil has been operated at a reduced thermal load using one winding. An experiment followed by an analysis was undertaken to determine if the OH-coil could be operated at full capacity without cooling the leaking segment by relying on conduction heat transfer to the neighboring cooled conductors. The analysis took into consideration the transient energy equations, including the effect of conduction between neighboring conductors. The axial conduction was modeled in the conductor, but was ignored in the coolant. An experiment was performed on the undamaged coil winding to determine the thermal conductance between neighboring conductors. The experiment consisted of passing hot water through adjacent cooling channels of two conductors and cold water through the cooling channels of the remaining two conductors of the same winding. The flow rate, inlet and outlet temperatures from each circuit were measured during the transient. From the experimental data and analysis, an average thermal conductance between the conductors was determined to be about 0.1 W/cm^2-C. Using the experimentally determined value of the thermal conductance, an analysis was performed on a coil winding consisting of one uncooled conductor and three cooled conductors. Results show that it is possible to operate the full OH-coil without cooling the damaged conductor to the desired thermal load of 20 MJ per pulse.

INTRODUCTION

DIII–D tokamak was built in 1986 and uses the ohmic heating coil fabricated for Doublet III in 1979. The DIII–D tokamak has been operating successfully with many upgrades. One serious problem has been that one of the conductors in the ohmic heating coil started leaking cooling water in July 1995.

The DIII–D OH-coil consists of two parallel windings of 48 turns each, cooled by water flow through the conductors. Each winding is made up of four parallel conductors (Fig. 1) about 200 m in length with coolant circuits of about 100 m in lenght. The coil is normally operated such that the energy input of about 20 MJ occurs nearly instantaneously (10 s) compared to the cooling time

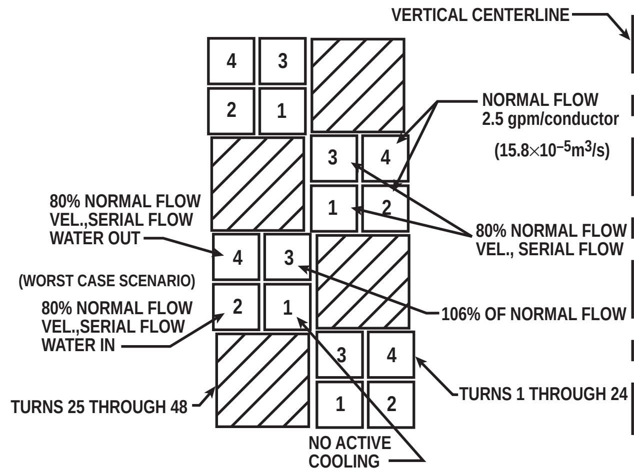

Fig. 1. Schematic cross section of a portion of the DIII–D OH coil showing proposed modified coolant flow

of ~600 s. The maximum allowed coil temperature is 80°C and the inlet cooling water has a maximum temperature of 25°C. The cooling water flow rate per conductor is 15.8×10^{-5} m^3/s (2.5 gpm), which results in a flow velocity of 1.6 m/s and a pressure drop of 0.52 MPa (75 psi). Since the leak, the ohmic heating coil has been operated with only one winding at a reduced energy input. The purpose of this work was to investigate cooling schemes which will allow the ohmic heating coil to be operated at the desired energy rating.

FORMULATION

Consider a conductor of area A_s and length L, cooled by coolant channel of Area A_w. The following basic relations can be written for transient temperatures of the conductor and the coolant (see nomenclature):

$$\left(\rho Cp\ A\right)_S \frac{\delta T_s}{\delta t} = q''' A_s - hP\left(T_s - T_w\right) + KW\left(2T_s - T_{n1} - T_{n2}\right) + k\frac{\delta^2 T_s}{\delta X^2} \qquad (1)$$

$$\left(\rho Cp\ A\right)_W \frac{\delta T_w}{\delta t} = -\left(\rho Cp\ A\right)_W V\frac{\delta T_W}{\delta X} + hP\left(T_s - T_w\right) \qquad (2)$$

The above formulation accounts for the axial conduction

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in the conductor but ignores it in the coolant. The radial temperature distribution in the copper is neglected because the Biot number: $Bi = h\ \delta_{cu}/k_{cu} = 0.3 < 1$.

Further, relations for the volumetric heating q''' and the heat transfer coefficient h are:

Heat Generation per unit volume:

$$q''' = \left(I/A_s\right)^2 \left[\sigma_o\left(1.0 + \alpha\ \ T_s - 20\right)\right]$$

$$q''' = 0.0 \text{ for } t>t_p$$

Heat Transfer coefficient:

$h = Nuk_w/d$
$Nu = 0.023(Re)^{0.8}(Pr\ )^{0.4}$
Re = Reynolds number = $\rho dV/\mu$
Pr = Prandtl number
Using these relations, a computer program was developed to perform this analysis. A semi-implicit numerical scheme was used to solve the equations.

EXPERIMENT

One of the important unknown variables required to solve the Eqs. (1) and (2) is the thermal conductance between the conductors. The gaps between the conductors (0.25 mm) are filled by epoxy glass composite. In the leads area the conductors are welded together in pairs at 30 cm intervals. Thermal conductance, K, between the conductors due to epoxy can be estimated as:

$K = k/\delta = 0.0025/0.025 = 0.1 = W/cm^2\text{-C}$

where

K = thermal conductance, W/cm^2-C
k = thermal conductivity of glass composite epoxy, W/cm-C
δ = thickness of glass composite epoxy

An experiment was performed with the undamaged coil winding to determine the actual thermal conductance. The inlet temperature of water to two of the conductors was introduced at about 51°C while inlet to the two other conductors was kept at about 21°C. Outlet temperatures were monitored as a function of time. The experiment was run until steady-state was achieved (in about 30 minutes). These conditions were used in the model described in the last section and the conductance between the leads was varied until agreement between experiment and analysis for the equilibrium temperature was obtained. From Fig. 2(a,b) we conclude that the average conductance in between the conductors is about 0.1 W/cm^2-C. The difference in analytical result and experimental measurements prior to steady-state may be due to heat transfer to a mass not modeled in the analysis. From analysis, it was estimated that the conductance in between windings was about 0.0015 W/cm^2-C.

ANALYSIS

The cooling system was originally designed for a parallel water flow rate of about $15.8\times10^{-5}\ m^3/s$ (2.5 gpm) through each conductor. However, due to some practical problems [1,2] now it is desirable to have flow in series for some conductors in addition to having the damaged lead uncooled. Fig. 1 identifies the worst combination from cooling considerations. Conductor 3 has 106% of the normal flow rate, conductors 2 & 4 are connected in series and hence have about 80% of normal flow rate and conductor 1 is not cooled.

First, an analysis was performed by ignoring heat transfer between neighboring conductors. Fig. 3 shows the axial temperature of conductor 3 as a function of time. The figure shows the peak temperature at the end of the current pulse and subsequent temperatures at intervals of 100 s. Fig. 4 shows similar results for conductors 2 & 4, which are connected in series. Conductor 3 (normal flow) is completely cooled to initial temperature in 10 minute intervals. However conductor 2 & 4 (connected in series) ratchet up in temperature during subsequent pulses. Fig. 5 summarizes the maximum temperatures of all three conductors after a number of pulses. This situation for the uncooled conductor is not acceptable.

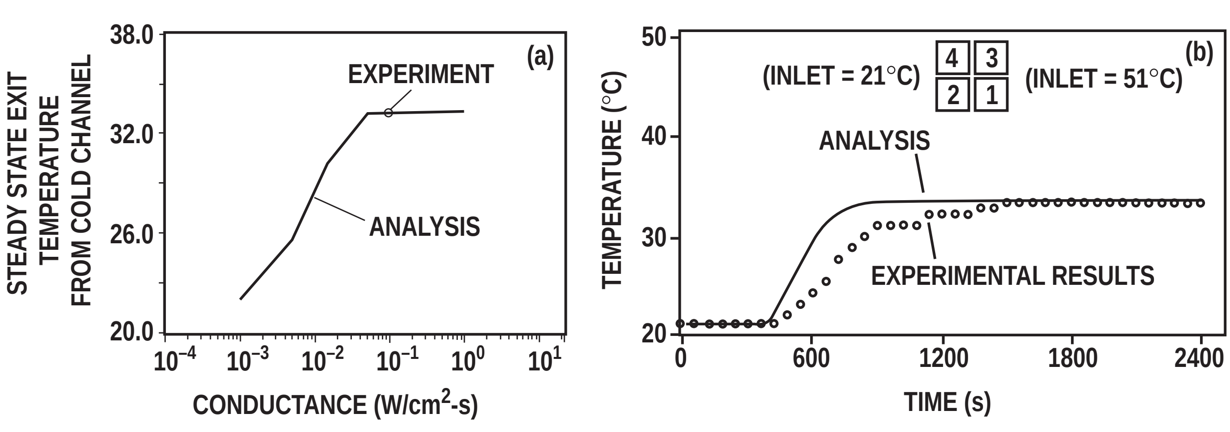

Fig. 2. (a) Relation between steady-state exit temperature of cold channel and thermal conductance between conductors, (b) Comparisons of exit temperatures between experiment and analysis (conductance in between conductors = 0.1 W/m^2-C and between windings = 0.0015 W/m^2-C).

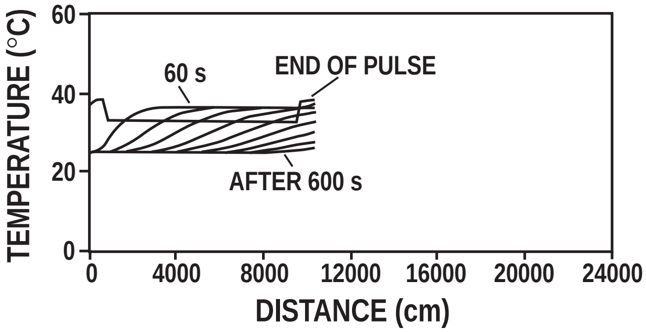

Fig. 3. Cooling time history with normal flow of 15.8×10^{-5} m^3/s (2.5 gpm). Curves are plotted at 60 s intervals.

summarizes the maximum temperatures of all three conductors after a number of pulses. This situation for the uncooled conductor is not acceptable.

An analysis was performed with inceasing values for the thermal conductance between the conductors. It was observed that for a conductance value greater than 0.05 W/cm^2-C, the uncooled conductor cooled down to temperatures of other conductors in the 600 s cooling time.

Fig. 6 shows the peak temperatures of three types of conductors discussed above for conductor-to-conductor conductance of 0.1 W/cm^2-C. The peak temperature in uncooled conductor after several pulses is less than 60°C.

Thus, this analysis shows that we can operate the ohmic heating coil without cooling the leaking conductor. However, one difficulty still remains to be overcome; the first 2 m length of the conductors are thermally isolated from each other. Analysis using the methods described here and by a finite element code COMOS [3] shows that temperature of this uncooled conductor region will ratchet up to 144°C. Hence, a separate cooling scheme to cool this part of the conductor by low pressure water or air is under development. Calculations show that an air flow of 9.4×10^{-3} m^3/s (20 CFM) in the leaking conductor will be adequate to keep the peak temperature below 60°C.

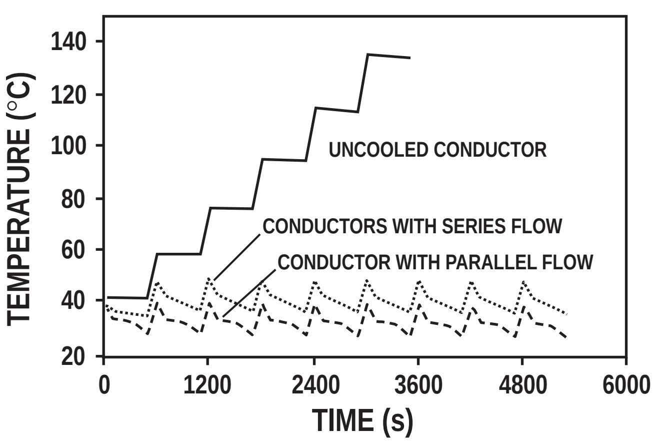

Fig. 5. Maximum temperature in each type of conductor at a given time with worst cooling combination <u>without</u> conduction in between conductors.

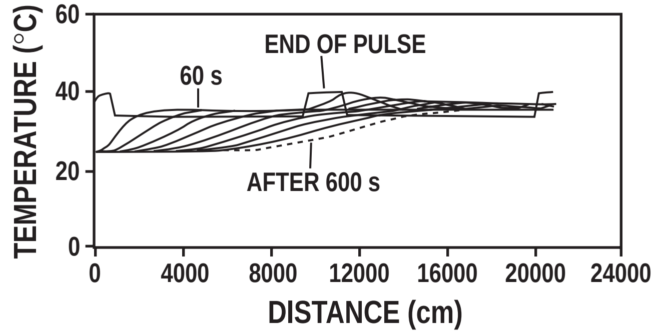

Fig. 4. Cooling time history with two conductors connected in series with 80% of normal flow. Curves are plotted at 60 s intervals.

CONCLUSIONS

The average thermal conductance between the conductors of DIII–D ohmic heating coil was modeled and measured directly. The results were found to be in good agreement at a value of is 0.1 W/cm^2-C.

The ohmic heating coil has a thermal input of 20 MJ in a relatively short time (5 to 10 s) followed by a cooling time of 10 min. The initial coil temperature is equal to water inlet temperature of about 25°C. The temperature rise during thermal input is only about 15°C and the maximum permissible epoxy temperature is 80°C. However, if the coil is not cooled between shots, the coil temperature ratchets up. Since the leaking conductor can not be cooled, it must rely on the conduction heat transfer from the neighboring conductors. This work has shown that there is a thermal conductance of about 0.1 W/cm^2-C between the conductors. A conductance value of more than 0.05 is sufficient to operate the ohmic heating coil without cooling the leaking conductor. Hence, DIII–D ohmic coil can be operated at originally designed thermal capacity of 20 MJ per pulse.

The first 2 m length, which is thermally isolated, can be cooled by low pressure water or air flow.

NOMENCLATURE

A = Area; m^2
Bi = Biot number = h δ_s/k_s
Cp = specific heat, J/kg-C
d = diameter of coolant channel; m

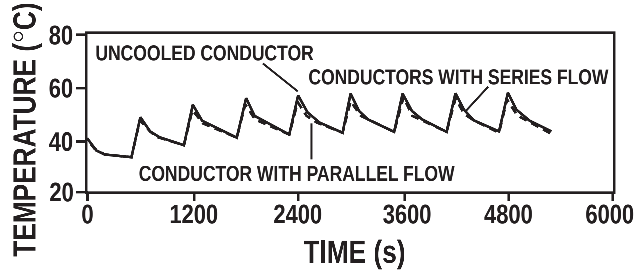

Fig. 6. Maximum temperature in each type of conductor at a given time with worst cooling combination <u>with</u> conduction in between conductors.

h = heat transfer coefficient; W/m^2-C
I = current; Amp
k = thermal conductivity, W/m-C
K = thermal conductance between neighboring turns, W/m^{2-}C
Nu = Nusselt number: hd/kw
P = cooling channel perimeter; m
q''' = heat generation rate; w /m^3
s,t = time; s
tp = pulse length; s
T = temperature; °C
ΔT = temperature difference; °C
V = flow velocity; m/s
W = width of contact between neighboring turns; m
X = axial distance; m
α = resistance coefficient
σ = resistivity; ohm-m
μ = viscosity; Pa-s
δ = thickness; m
<u>subscripts</u>
s, cu = copper
w = water
n1, n2 = neighboring channels

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