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Thermal Analysis of DIII-D Coils for Long Pulse Operation*

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***Abstract*—DIII-D tokamak will be operated at higher magnetic flux and longer pulse lengths starting in 2006. Hence the water-cooled copper coils will be subjected to higher currents and longer pulse length. In order to insure that the coils do not overheat during such an operating condition, a systematic program of analysis and experiments is being implemented. F8A coil has been operated with limited I^2t, due to its long cooling path and limited coolant flow rate. The geometry of this coil was modeled which accounted for the forced convective heat transfer to the coolant, conduction heat transfer between the windings, heat loss to the atmosphere and change in coolant temperature as a function of distance. The model was used to determine the flow rate required and time to cool down the coil for higher currents and longer pulse operation without exceeding the safe temperature limits.**

Keywords–Thermal analysis, copper coils, cooling

I. INTRODUCTION

The F8A coil consists of 58 turns. The coil is cooled by two parallel water circuits. Each set of 29 windings is arranged such a way that there is conduction heat transfer between adjacent conductors through the electrically insulating epoxy (Fig. 1). The conductor is rectangular with a circular coolant hole.

The flow path of the pancake construction of the F8A coil is shown in Fig. 2. The 29 windings are electrically as well as for water flow, connected in series. The flow goes from winding 1 to 6 at one level of pancake and then through 7 to 12 at the next level. The model accounts for this. The conduction through the epoxy is tricky to model. For example, the winding 1 conducts to 2 and 12; winding 11 conducts to 10, 12, 2 and 14. This has been accounted for in the analysis model.

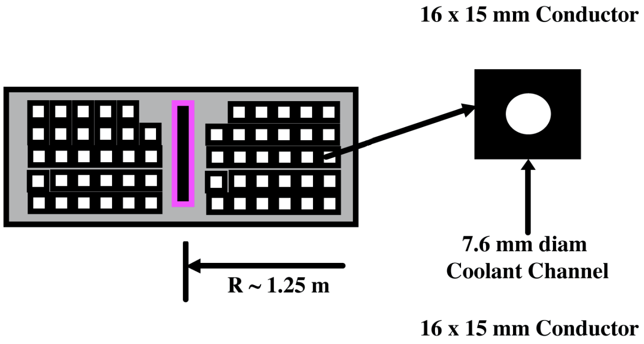

Figure 1. F8A coil configuration.

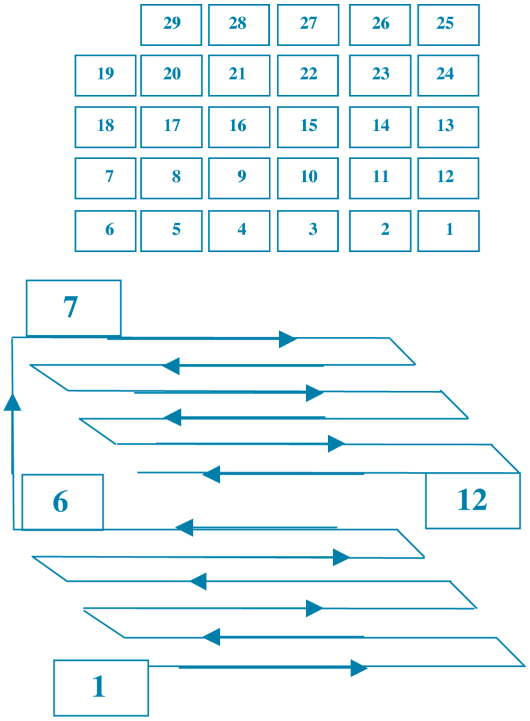

Figure 2. Flow and conduction paths in the F8A coil.

This geometry was modeled which accounted for the forced convective heat transfer to the coolant, conduction heat transfer between the windings, heat loss to the atmosphere and change in coolant temperature as a function of distance. The analysis took into consideration the transient energy equations and axial conduction in the conductor. The effect of electrical leads on the coolant outlet temperature was also accounted for. The model was verified by comparison to the measurements done during operation. Additional experiments were performed with hot water flowing through the coil.

The model was used to determine the flow rate required and time to cool down the coil for higher currents and longer pulse operation without exceeding the safe temperature limits.

II. ANALYSIS

The model described in Refs. 1 and 2 was modified to include the conduction heat transfer between adjacent windings.

Consider a conductor of area *As*, cooled by a coolant channel of area *Aw* and perimeter *P* (Fig. 3). The relations transient temperatures of conductor *Ts* and water *Tw* are:

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Conductor:

$$(\rho CpA)s\frac{\partial Ts}{\partial t} = q'''As - hP(Ts - Tw) - Kw(2Ts - Tsn1 - Tsn2) \ ,$$

Water:

$$(\rho CpA)\,w\frac{\partial Tw}{\partial t} \ = \ -\,(\rho CpA)wV\frac{\partial Tw}{\partial x} + hP(Ts - Tw) \ ,$$

where:

A = area
Cp = specific heat
h = heat transfer coefficient
Kw = winding to winding conductance
P = perimeter of the coolant channel
q''' = volumetric heat generation rate in the conductor
T = temperature
t = time
V = flow velocity
x = distance
ρ = density
s = conductor
w = water
$sn1, sn2$ = neighboring conductor

The conductors are wound such that each turn can conduct heat to two to four other turns (Figs. 1 and 2). The thermal capacity of the insulation and structure enclosing the coil is about 50% of the thermal capacity of the conductor. After each pulse, the total joule loss is diffused in the stucture in about 20 s. The analysis takes both these effects into account.

In order to perform a meaningful analysis of the F8A coil, a number of parameters must be determined. Some of these can be calculated but others must be determined by a calibration experiment.

1. Thermal Capacity:

   Although the area and length of the conductor is known, the area of the insulation and structure is not negligible.

   - Area of Cu = 109 cm^2
   - Area of insulation and structure = 105.6 cm^2
   - Therefore, total thermal capacity ~150% Cu thermal capacity.
   - Thus the equivalent thermal capacity of the coil is ~150% of the copper.

2. Fouling:

   The heat transfer coefficient for flow through a conductor can be calculated by known correlations [3]. However, the coil has been in use for several years and the effect of fouling must be calculated. The fouling resistance [3] for a flow velocity of ~1 m/s and water temperature of < 50°C is 2 cm^2-C/W. This reduces the effective heat transfer coefficient by about 50%.

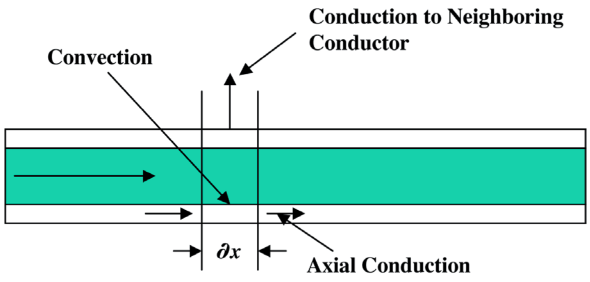

Figure 3. The unit cell for analysis.

3. Effect of Electrical Lead:

   The inlet and outlet part of the conductor is connected to an electrical lead. A separate FE analysis of this geometry was performed. It was concluded that there was about 1°C difference between the measured and actual water temperature due to thermal capacity of the electrical lead.

4. Winding-to-Winding Conductance:

   As seen from Fig. 1, winding-to-winding heat transfer occurs by conduction through epoxy. In order to determine the value of this conductance (Kw) an experiment was conducted. The experiment consisted of flowing hot water through the outer winding of the coil and measuring flow rate, inlet water temperature and outlet water temperature as a function of time.

The experimental flow and inlet conditions were input to the analysis model and conductance values were determined by parametric study. Fig. 4 shows the comparison between measured and calculated outlet temperatures for Kw=0.02 $\text{W/cm}^2/\text{C}$.

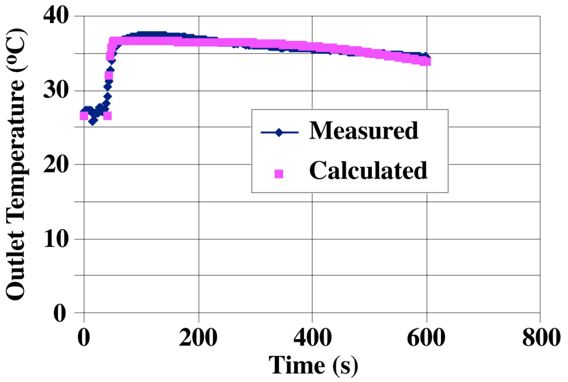

Figure 4. Comparison of analysis and experiment for Kw = 0.02 $\text{W/cm}^2/\text{C}$.

These values were confirmed by a second experiment with higher flow rate.

3. DIII-D OPERATION

F8A coil has limited flow due to its long length. Also the only measurement available is an outlet water temperature from the coil. Since exact relation between outlet temperature and coil temperature was not known, the coil has been operated till now at an I^2t (amp^2-sec) value of $<1.5\text{x}10^8$.

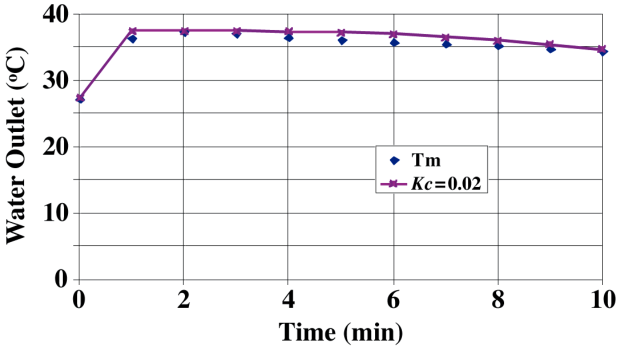

Figure 5. Analysis of shot 120675 confirms method and parameters (I^2t = 1.36 x 10^8, 0.75 gpm).

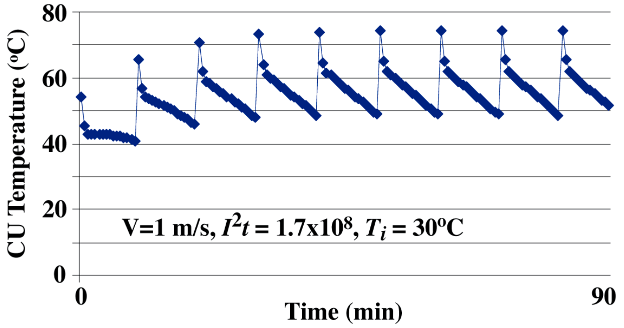

Figure 6. Calculated conductor temperatures after many pulses.

3.1. *Operation for Higher I^2t*

Fig. 5 shows the comparison between measured water outlet temperature and the analysis for shot 120675. Parametric study revealed that increasing the heat transfer coefficient had very little effect on increasing the cooling rate. This is because the cooling rate is limited by flow rate rather than the heat transfer coefficient due to long length of the conductor and hence the large heat transfer area. However, the allowable I^2t of the coil can still be increased by, (1) reducing the inlet temperature, (2) increasing the flow rate, and (3) by increasing the time between pulses. Cooling rate of the conductor in *J/s* is:

$$Q' = m'Cp\Delta T1 = hA\Delta T2 \quad .$$

Where:

Q' = rate of heat transfer
m' = flow rate
Cp = specific heat of coolant
$\Delta T1$ = coolant temperature rise
h = heat transfer coefficient
A = area of heat transfer
$\Delta T2$ = film drop

For a F8A coil:

$$hA / m'Cp = 4Nu / (\mathrm{Re\,Pr})(L/D) = 52 \gg 1$$

Hence, the cooling is limited by flow rate rather than heat transfer. Increasing the heat transfer by a factor of 2 (acid cleaning), without increasing the flow (acid cleaning) will have little effect on cooling rate.

The maximum allowable temperature of the copper conductor is 75°C due to temperature at which the coil was cured. The peak temperature limitation must be satisfied after many pulses, as shown in Fig. 6 for 10 minutes repetition rate.

Table 1 lists how the I^2t can be increased by choosing the cooling parameters. The parameters are shown in Fig. 7.

TABLE I. EFFECT OF COOLING PARAMETERS ON ALLOWABLE I^2t

Flow (gpm)	Inlet Temperature (°C)	Cooldown Time (min)	I^2t for 75°C Peak Cu Temperature	Maximum Calculated Outlet Water Temperature (°C)
0.75	30	10	1.7 x 10^8	63
0.75	30	20	2.6 x 10^8	58
0.75	20	20	3.2 x 10^8	51
1.00	30	20	2.9 x 10^8	55

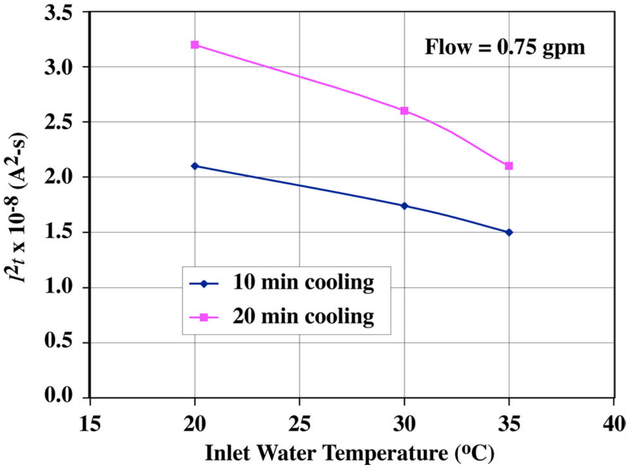

Figure 7. Calculated conductor temperatures after many pulses.

CONCLUSIONS

The F8A coil can be safely operated at higher I^2t by increasing the flow rate, reducing the inlet temperature or by increasing the time in between pulses. The parameter range to operate the coil at higher I^2t has been identified.

Increasing the heat transfer coefficient (by acid cleaning) without increasing the flow will have no effect.

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