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THE FOLLOWING CALCULATIONS DETERMINE THE PRESSURE DROP, TEMPERATURE RISE, AND TIME TO COOL A COIL GIVEN THE FLOW-RATE OF COOLING WATER, GEOMETRY OF THE COIL, AND AVGERAGE CURRENT FOR A SPECIFIED PULSE LENGTH.

First Calculate the pressure drop through a coil of length L.

$\rho_w := 8.28 \cdot \frac{lb}{gal}$ $c_p := 1 \cdot \frac{BTU}{(lb \cdot R)}$ water $\mu_w := 20.92 \cdot 10^{-6} \cdot lbf \cdot \frac{sec}{ft^2}$ water (ref. 3-35 Marks HandbooK)

$\varepsilon_{cu} := 10 \cdot 10^{-6} \cdot ft$ for drawn copper tube $\varepsilon_{pipe} := 150 \cdot 10^{-6} \cdot ft$ for steel pipe (ref. 3-56 Marks)

$Q = 162.773 \frac{cc}{sec}$ $Q = 2.58 \frac{gal}{min}$ Flow rate of cooling water

$d_p = 0.306\,in$ $d_p = 0.777\,cm$ inner diameter of cooling passage for a round cross-section

$L = 538.886\,cm$ hydraulic length of opening under evaluation

$\mu := \mu_w$ $\rho := \rho_w$ $\varepsilon := \varepsilon_{cu}$ Input Values $\nu := \frac{\mu}{\rho}$

Calculate the Reynolds # using the velocity and diameter. Use the hydrolic diameter if it is not a round cross-section.

For a round pipe $d_p = 0.306\,in$ $Area_p := \left(\frac{d_p}{2}\right)^2 \cdot \pi$

$D := d_p$ $A := Area_p$ Input Hydrolic Diameter and Area $A = 0.074\,in^2$

$A = 0.474\,cm^2$

Calculate the Reynolds #

$v := \frac{Q}{A}$ $v = 11.256 \frac{ft}{sec}$ $Re := D \cdot \rho \cdot \frac{v}{\mu}$ $Re = 2.641 \times 10^4$

Now find the friction factor using the Reynolds #, the Relative roughness, and the diameter

$f_l := \frac{64}{Re}$ $f_l = 2.423 \times 10^{-3}$ for <u>laminar flow</u>

To find f.t for <u>turbulent flow</u> calculate the relative roughness, e/d, and use along with the Re # to look up f on the graph (pg. 3-55 Marks or pg. A-24 of the Crane tech. manual), or use the following formula:

Colebrook's implicit formula, solved iteratively:

$fr := .01$ seed value for iteration

Given $\frac{1}{\sqrt{fr}} = -2 \cdot \log\left(\frac{\frac{\varepsilon}{D}}{3.7} + \frac{2.51}{Re \cdot \sqrt{fr}}\right)$

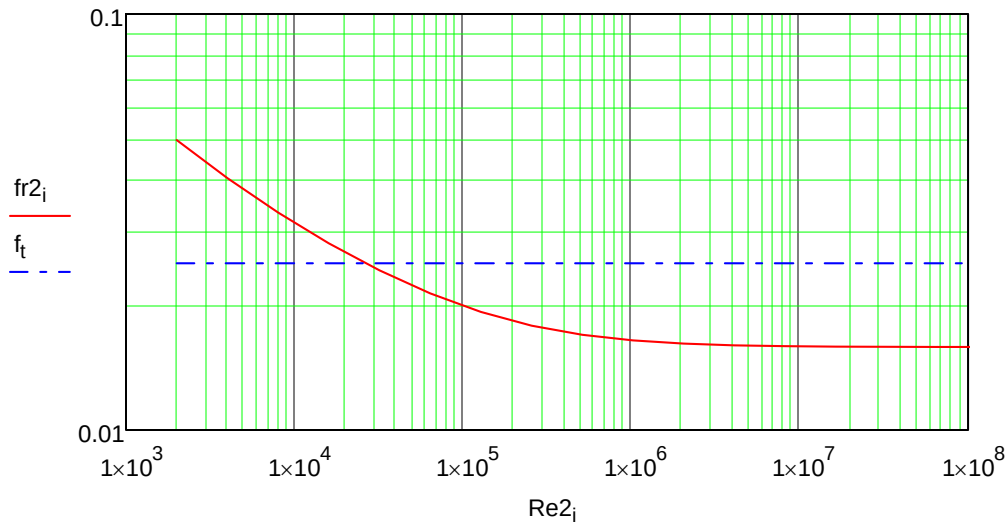
$f(\varepsilon, D, Re) := Find(fr)$

$f_t := f(\varepsilon, D, Re)$

$f_t = 0.025$ Turbulent friction factor

Graph Reynolds # vs Friction Factor for turbulent flow $\frac{\varepsilon}{D} = 3.922 \times 10^{-4}$ $Re = 2.641 \times 10^{4}$

$i := 0 .. 16$ $Re2_i := 2000 \cdot 2^i$ $fr2_i := f(\varepsilon, D, Re2_i)$



Referance pg. 3-55 Marks to determine if flow is laminar or turbulent Generally turbulance begins at Re>2000

$f := if(Re > 2000, f_t, f_l)$ $Re = 2.641 \times 10^{4}$ $f_t = 0.025$ $f_l = 2.423 \times 10^{-3}$

$f = 0.025$

Now calculate the head loss and pressure drop across the length of pipe l

$H_f := \frac{v^2}{2 \cdot g}$ $Q = 162.773 \frac{cc}{sec}$ $Q = 2.58\,GPM$ $d_p = 0.306\,in$ $L = 17.68\,ft$ $m := Q \cdot \rho$

$h_f := f \cdot \left(\frac{L}{D}\right) \cdot H_f$ $p := h_f \cdot \rho \cdot g$ $H_f = 1.969\,ft$ $H_f \cdot \rho \cdot g = 0.847\,psi$

$h_f = 34.353\,ft$ $p = 14.776\,psi$ $v = 11.256 \frac{ft}{sec}$ $m = 0.356 \frac{lb}{sec}$

Calculate the power into the coil for a T_{in} pulse length

$c_{pcu} := .092 \cdot \frac{BTU}{(lb \cdot R)}$ $c_{pcu} = 97.065 \frac{(watt \cdot sec)}{(lb \cdot R)}$ for copper $T_{in} = 8.5\,s$ $L = 17.68\,ft$

$dx = 2.23\,in$ $dy = 2.23\,in$ $area_{cu} := dx \cdot dy - A$ $I = 1.35 \times 10^{5}\,amp$

$r := 10.37 \cdot ohm \cdot \left(\frac{cmil}{ft}\right)$ $r = 8.145 \times 10^{-6} \frac{in^2}{ft} \cdot ohm$ for copper

$\rho_{cu} := .322 \cdot \frac{lb}{in^3}$ $\rho_{cu} = 8.913 \frac{gm}{cm^3}$ for copper

$r_t := \frac{r}{area_{cu}} \cdot L$ $r_t = 2.939 \times 10^{-5}\,ohm$ total resistance for length of coil

$P_{in} := I^2 \cdot r_t$ $P_{in} = 5.356 \times 10^{5}\,watt$ This is the power into the coil

These formula calculate the rise in temperature of a conductor of area A after time elapsed = T_{in}. It assumes all energy is absorbed by the thermal mass of the copper ie there is no heat transfer away from the conductor.

$Vol := L \cdot area_{cu}$ $\quad Vol = 1.039 \times 10^3\, in^3$ $\quad Vol = 1.703 \times 10^4\, cm^3$

$dt_{cu} := \dfrac{T_{in} \cdot P_{in}}{\rho_{cu} \cdot Vol \cdot c_{pcu}}$ $\quad dt_{cu} = 140.145\, R$ $\quad dt_{cu} = 77.858\, K$ $\quad$ This should not exceed 70 K

Calculate the length of time required to cool the coil dt_{cu}

$P_{cool} := m \cdot c_p \cdot dT_{water}$ $\quad P_{cool} = 2.536 \times 10^3 \dfrac{joule}{sec}$ $\quad$ This is the power taken out of the coil by the water assuming a temperature increase in the water of dt.water

$T_{cool} := \dfrac{P_{in} \cdot T_{in}}{P_{cool}}$ $\quad T_{cool} = 29.927\, min$ $\quad$ The time it will take for the water to pull out the energy imparted to the copper during a T_{in} sec. pulse assuming a delta T of the water = dT.water

A precise calculation of the pressure, velocity flow and copper temperature rise is in agreement with the FCool calculation NSTX-CALC-132-10-00. The time to cool the coil was verified to be within the requirement with a worst case calculation that shows the cooling time to be much lower than 1800 seconds and estimated to be within the range specified in the FCool Caluclation. With a repetion rate of a one second pulse every 1800 seconds at 135000 amps the intial temperature rise is 140F. If the delta T of the water was only 3.8C the heat removed by the water would be in equilibrium with the average heat imparted to the coil over the 1800 sec rep rate. The average delta T of the water will be much higher about a third of the way to the maxium 140F delta T of the coil and the time to cool the coil will be much less than the requirement of 1800 secs. This is consistent with the FCool calculation.

INPUTS

$L \equiv 17.68\text{ft}$ $\quad L = 17.68\,\text{ft}$ — Total length of coil

$dx \equiv 2.23\text{in}$ — Equivalent Width of coil cross-section

$dy \equiv 2.23\text{in}$ — Equivalent Height of coil cross-section

$d_p \equiv .306\text{in}$ — Diameter of hole for cooling water

$Q \equiv 2.58 \cdot \frac{\text{gal}}{\text{min}}$ — Volume flowrate of cooling water

$T_{in} \equiv 8.5 \cdot \text{sec}$ — Length of pulse

$I \equiv 135000 \cdot \text{amp}$ — Average current during pulse

$dT_{water} \equiv 3.75\text{K}$ — Assumed increase in water temperature through the coil

OUTPUTS

$P_{in} = 5.356 \times 10^5\,\text{watt}$ — Power dissipated during pulse

$A = 0.074\,\text{in}^2$ — Area of hole for cooling water

$\text{area}_{cu} = 4.899\,\text{in}^2$ — Cross-sectional area of cooper used to calculate coil ressistance

$v = 343\,\frac{\text{cm}}{\text{sec}}$ $\quad v = 11.3\,\frac{\text{ft}}{\text{sec}}$ — Velocity of cooling water through coil

$p = 14.8\,\text{psi}$ — Pressure drop of water through coil

$dt_{cu} = 77.9\,\text{K}$ $\quad dt_{cu} = 140\,\text{R}$ — Temperature increase of coil due to pulse current neglecting cooling

$T_{cool} = 1.796 \times 10^3\,\text{sec}$ — Time required for water to cool the coil given dT_{water}

$\frac{L}{v} = 2\,\text{sec}$ — Time for water to make one complete pass

$\frac{I}{\text{area}_{cu}} = 2.755 \times 10^4\,\frac{\text{amp}}{\text{in}^2}$ — Current Density