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Optimization of wall thickness for water-cooled hollow conductor drive coils in human-sized MPI

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Abstract

The reduction and removal of heat dissipated in the drive coil emerges as a major concern when Magnetic Particle Imaging is scaled to human size. The low AC-resistance of Litz wire can reduce the power that generates the heat, but cooling Litz wire bundles can pose a challenge. Hollow conductors with axially flowing coolant present an attractive alternative, but because of skin and proximity effects, the wall thickness is a critical design parameter affecting both the heat created and its rate of removal. Here, we introduce and experimentally validate an analytical method for calculating drive coil heating and optimizing the wall thickness. We demonstrate that the optimal wall thickness provides a 3.3 times improvement in cooling efficiency versus the not optimized case for the particular drive coil investigated for a fixed pressure with only marginal changes to the coil resistance. A 3.3 times improvement in cooling efficiency would allow for ~ 1.8 times more current for the same coil temperature rise, and thus higher drive fields.

I. Introduction

As Magnetic Particle Imaging grows to human-scale, a chief concern is how to dissipate the heat in the drive coils. Litz wire is popular for its low AC-resistance and one method of cooling Litz wire is by surrounding it in a pressurized coolant bath e.g., water or oil. However, this method scales poorly to human-sizes since the hoop stresses on the containing structure grow with radius and would need to have very thick walls. Further, water flowing over the surface of wires only cools the outermost layer. Ambient air, or convection are similarly poor solutions when imaging at high duty cycles.

Hollow conductors present an attractive alternative, as the flowing (and necessarily pressurized) coolant is in the interior cavity of the copper conductor (which having small radii are proportionally much stronger), and have effectively perfect thermal contact with the coolant. However, there is little literature on how to optimize the wires for minimum temperature rise. The minimum resistance wall thickness for a long straight wire in isolation can be analytically approximated [1]. Yet, water viscous resistance to flow is approximately inversely proportional to the pipe's inner diameter to the fourth power. The wall thickness is thus a critical parameter which influences both the effective AC-resistance and

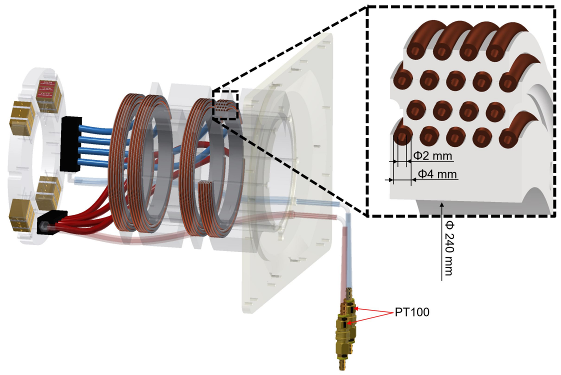

Figure 1: Schematic of the drive coils and location of the PT100 temperature sensors

the fluid resistance (water cooling efficiency).

The overall goal of this work is first to validate a method for predicting the drive coil's resistance and temperature rise, and then choose the wall-thickness for these hollow conductors that minimizes the temperature rise of the coil.

II. Methods and materials

Figure 1 shows the schematic of the drive coils used for the test, which were designed for our human head MPI [2]. There are four 18-turn drive coil modules, each with a parallel water coolant circuit. The wire used has an outer diameter(OD) of 4 mm and 1 mm wall thickness. The coolant is distributed from the manifolds in the back. The total length of wire on each module is 16.3 m. The AC-resistance of each module is 321.5 mΩ. This results in a power dissipation of 154 W when operated at 21.9 A_{RMS}. However, according to FEMM 4.2 simulations, about 6.5% of the power is dissipated in the shield surrounding the drive coil, so we estimate 144 W being dissipated in the wires. This was experimentally validated by measuring the inlet and outlet water temperatures (with PT100 sensors) and the flow rate and pressure drop. The fluid viscous resistance is calculated with an analytical formula presented in Ref. [3] (Eqn. 13).

The effective conductor area, A_e, considering a simple exponential decay of current from the outer surface is approximately:

$$A_e \approx 2\pi \int_{R_i}^{R_o} e^{-(R_o-r)/\delta} \cdot r\,\mathrm{d}r \tag{1}$$

Where R_i and R_o are the inner and outer radii respectively and δ is the skin depth. More accurate models are available [1, 4], but for this context the simplicity is preferred. The power can be approximated as:

$$P = \frac{I_{\mathrm{RMS}}^2 \rho L}{A_e} \tag{2}$$

Where ρ is the resistivity of the conductor, and L is the length of wire. As the wall thickness gets thicker than δ, A_e becomes only marginally larger, but the fluid resistance to flow rapidly increases with R_i^4, and the mass flow rate is roughly proportional to pressure drop and inversely proportional to the fluid viscous resistance ($\dot{m} \propto$ pressure drop/viscous resistance). As the wire is very thin ($<\delta$) the wires resistance becomes excessively large. The steady state total rise in wire temperature (ΔT) is expressed assuming no heat loss as:

$$\Delta T = \frac{P(A_e, L)}{\dot{m}(R_i, L) C_p} \tag{3}$$

Where $\dot{m}(R_i, L)$ is the mass flow rate of water (kg/sec) and C_p the specific heat of water (J/(kgK)). The temperature rise can be written as being inversely proportional to both A_e and R_i^4, i.e.

$$\Delta T \propto A_e^{-1} \cdot R_i^{-4} \tag{4}$$

As an illustrative case, the full analytical model (using the equations in Ref. [3]) is compared to this simple proportionality for a 4 mm OD hollow conductor with wall thickness ranging from 0.04 mm to ~1.5 mm, where the optimum point is the minimum ΔT. The best-case wall thickness is then simulated for the drive coil that uses 4 mm OD hollow conductor, and the predicted resistance and temperature rises are compared.

III. Results

Figure 2 shows the measured inlet and outlet temperatures. The predicted mass flow rate given an inlet pressure of 138 kPa(20 PSI) is 2.6 g/sec, whereas the measured flow rate is 1.7 g/sec, and the discrepancy is likely due to the pressure sensor being far upstream of the coils themselves and connections adding fluid resistance. Using the measured mass flow rate, and resistance simulated from FEMM 4.2 for the power (144 W), we predicted a 20.23 °C rise, which is very near the 19.24 °C measured.

Figure 3 shows the expected rises in temperature as a function of wall thickness, normalized to the minimum value. The two approaches agree reasonably well in finding the optimum solution. Table 1 shows the results from the FEMM 4.2 simulation comparing the 2.5 skin depths case (thickness of the wire used) to the optimized wall thickness. The cooling efficiency($\Delta T/I^2$)improvement for the human system is 3.25 times.

IV. Discussion and conclusion

Here, we show a method for the predicting the heating of MPI drive coils cooled with water as well as a simple approach for determining a near-optimum wall thickness. The measurements on the human MPI drive coil showed

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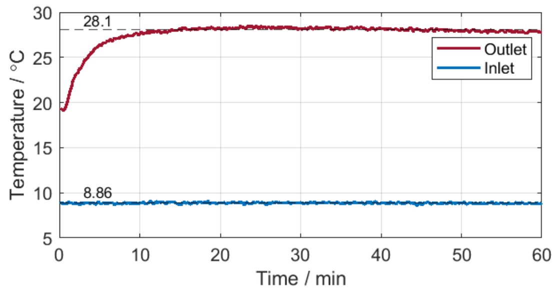

Figure 2: Measured inlet and outlet water temperatures for 21.9 A_{RMS} at 100% duty cycle over one hour

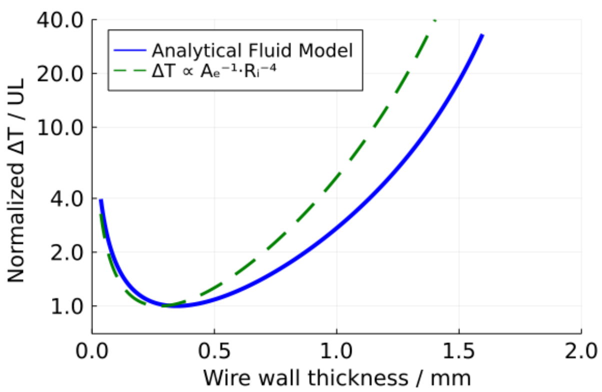

Figure 3: Expected rise in coil temperatures normalized to the minimum value using the full analytical formula for water flow (blue) and the simple proportionality in Eqn. 4(green dashed line). The minimum value for the analytical model is a wall thickness of 0.34 mm and for the proportionality is 0.28 mm.

that this method for prediction yielded reasonably accurate findings, and the difference between measured and simulated is expected given the losses in the manifolds and other connectors in between the pump and drive coils themselves. The wall thickness, is also a function of outer diameter, which was not discussed here as other factors come into play such as packing density, target impedance, proximity to other conductors, etc.

While having thinner walls might increase resistance in the case of a long straight wire, for the tightly wound solenoid, proximity effects dominate and the resistance in some scenarios may be effectively unchanged. The greatest drawback limiting the accuracy of this method is the neglecting of proximity effects from nearby wires. To model this, a full finite element method simulation would likely need to be done. This is unlikely to substantially change the outcome as the solution lays in a fairly flat minimum region and one could err on the side of thinner wire to account for it. Lastly, the analytical

	2.5 skin depths (1 mm)	Optimized (340 μm)
Resistance / mΩ	322	400
Mass flow / g/s^{-1}	2.6	10.5
$\Delta T/I^2$ / °CA^{-2}	0.03	0.009

Table 1: Resulting efficiency for the non-optimized and optimized drive coils on the human MPI system. The mass flow is simulated for 20 PSI and a wire length of one module 16.3 m. The resistance is for only one of the four modules.

optimization seeks the minimum change in wire temperature, not minimum resistance, as coil heating is often the limiting factor not total power delivered. A 3.3 times improvement in cooling efficiency ($\Delta T/I^2$) would allow for 1.8 times the drive current, and thus drive field.

We present this novel approach for determining a near-ideal wall thickness for a hollow conductor with a fixed outer diameter. Having a simple analytical model to predict wire thickness is powerful design tool and far more efficient strategy rather than relying on finite elements methods or multi-physics simulations of the full system which are computationally burdensome and do not typically include the fluid dynamics.

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Author's statement

Conflict of interest: Authors state no conflict of interest.

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