Experimental validation of an improved analytical temperature distribution model for gradient coils

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Introduction: The operation of gradient coils typically involves large currents being driven in resistive copper wires. Consequently this can lead to considerable Ohmic heating of the gradient coils and their surroundings, including the shim coils and RF systems, which can result in gradient failure, image distortion or signal dropout. Of primary concern are gradient hot spots, which occur in regions of high current density, or equivalently, where the coil windings are closely spaced [1]. While et al. [2] present a theoretical model for predicting the spatial and temporal temperature distributions of gradient coils, for a wide variety of geometries and thermal material property considerations. This model was also used to provide a temperature constraint in a non-linear gradient coil optimisation routine [3]. Other gradient coil design methods have been proposed that target coil winding spacing directly [4,5]. In the present work, a modified version of the temperature distribution model of [2] is presented that more fully accounts for the internal energy storage of the entire system as well as the radiative loss of heat at the outer surface of the gradient coil, and also includes an effective thermal conductivity of the copper layer to more accurately account for insulation properties of the epoxy material. The predictive power of the model is demonstrated by comparing the simulation results to images obtained using a thermal imaging camera for two inherently different gradient coil designs.

Temperature model: The gradient coil is represented by a cylindrical copper sheet of radius r_c, length $2L$ and thickness w. This copper cylinder is embedded in a number of cylindrical layers of different materials. To match the experimental setup that follows, three additional layers are considered ('i', 'n' and 'o') that extend radially from r_i to r_n, from r_n to r_c, and from r_c to r_o, respectively. A heat equation is constructed by considering Ohmic heating as a result of current density $\boldsymbol{j}$ (A/m), heat conduction across the copper layer, radial conduction through the other three layers, and radial convection and radiation to the environment:

$$\sum_{l=i,n,c,o}\left[\rho_{dl}c_{hl}\Delta r_l\breve{r}_l\right]\frac{\partial T^*}{\partial t} = \left(\frac{k_c k_n}{\alpha k_n+(1-\alpha)k_c}\right)\nabla^2 T^* + \frac{\rho_r}{w^2}\boldsymbol{j}\cdot\boldsymbol{j} - \frac{h_t}{w}T^* \qquad (1);$$

$$h_t = \left[\frac{\Delta r_n}{k_n} + \frac{r_c\Delta r_i}{r_n k_i} + \frac{r_c}{r_i h_i}\right]^{-1} + \left[\frac{\Delta r_o}{k_o} + \frac{r_c}{r_o(h_o+\varepsilon_o h_r)}\right]^{-1} \qquad (2)$$

Here T^* is the temperature difference between the coil and the environment, ρ_{dl}, c_{hl}, Δr_l, $\breve{r}_l$ and k_l, are the density, specific heat, thickness, midpoint and thermal conductivity of the corresponding layer, k_c and ρ_r are the thermal conductivity and resistivity of the copper layer and α is the proportion of copper to epoxy in that layer. The parameter h_t is the total heat transfer coefficient and represents the radial cooling in the system, h_i and h_o are convective heat transfer coefficients for the inner and outer surfaces, h_r is the approximate radiative heat transfer coefficient and ε_o is the emissivity of the outer surface. The spatial temperature distribution can be obtained by solving the steady-state form of Eq. (1), and this is achieved using Fourier series [2]. An approximate solution for the temporal behaviour of the maximum coil temperature can also be obtained by linearising the first term on the right hand side of Eq. (1). This yields an inverse exponential function of time and allows rise-time to be investigated.

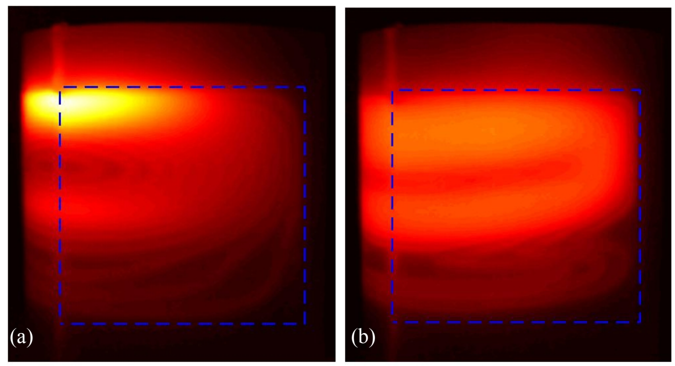

Fig. 1: Experimentally measured temperature: (a) min(P), (b) minimax|J|.

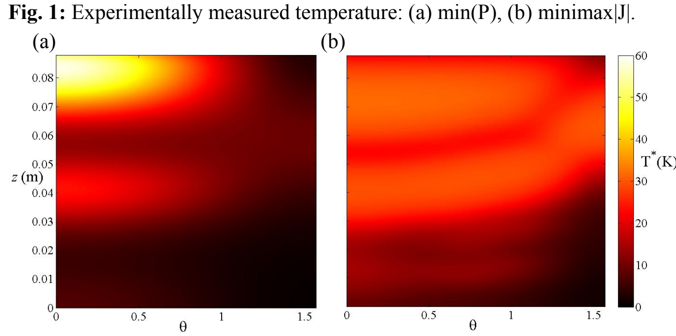

Fig. 2: Simulated temperature (above ambient): (a) min(P), (b) minimax|J|.

Experimental setup: To test the accuracy of the model, simulations were compared to experimental temperature data obtained from the operation of two prototype gradient coils. These two coils were chosen to have inherently different coil winding structures such as to provide a rigorous test for the model. The first was a standard minimum power design and the second was a minimax|J| coil design of Poole et al. [5]. The coil windings for both coils were milled on 0.35 mm flexible PCB with an 18 μm copper layer. These were scaled to fit around the outside of a PVC pipe of radius 55.5 mm (thickness 3 mm) with an effective coil length of 176 mm, and fastened using electrical tape [6]. Drive currents of 1.90 A and 1.91 A (RMS) at 100 Hz were passed through the min(P) and minimax|J| windings, respectively, in series, such that gradient strengths were matched. A NEC F30 thermal imaging camera was used to take temperature measurements as the two coil systems reached thermal equilibrium.

Results and discussion: Fig. 1 shows the thermal imaging results for the two coils at thermal equilibrium (after 45 min). The minimum power coil in Fig. 1(a) displays a hot spot in the location of dense coil windings with max(T^*) = 58.2 K (above ambient). In contrast, the minimax|J| coil in Fig. 1(b) displays a spread out temperature distribution and much lower max(T^*) = 32.9 K. Fig. 2 shows the corresponding simulation results from using the spatial temperature distribution model and inputting the appropriate geometry parameters and thermal material properties for each layer (PVC pipe, FR4, copper, PVC tape). The heat transfer coefficients were chosen assuming convective air cooling, with h_i = 3 and h_o = 5.5 W/m^2/K [1]. The radiative heat transfer coefficient was chosen approximately to be h_r = 7 W/m^2/K for the min(P) coil and h_r = 6.5 W/m^2/K for the minimax|J| coil (ε_o = 0.9). The copper proportion parameter was selected to be α = 0.995, which meant that the copper layer had an effective thermal conductivity of 41.29 W/m/K. This high value was chosen approximately, corresponding to the densest regions of the coil where the heating is greatest. Comparing Fig. 2 to Fig. 1 we observe excellent qualitative agreement for both coil types. Note that the images in Fig. 1 have not been unwrapped from a cylindrical shape and have not been corrected for any barrel-distortion caused by perspective issues related to camera placement. This will be addressed in further work such that the results can be compared quantitatively in detail. The simulations predict max(T^*) = 58.8 K for min(P) and max(T^*) = 31.8 K for minimax|J|, which compare well to the experimental values. Fig. 3 displays the peak temperature measurements obtained over the first 8 min of operation, along with the simulation predictions for the approximate temporal behaviour of hot spot temperature. The temporal simulation solves only the linearised form of Eq. (1), however it nevertheless provides a reasonable prediction of rise-time to thermal equilibrium. In conclusion, the presented model performs well at predicting both the spatial distribution and rise-time of coil temperature. The model can be adapted straightforwardly to consider a wide range of coil structures and materials, and provides a great utility prior to manufacture.

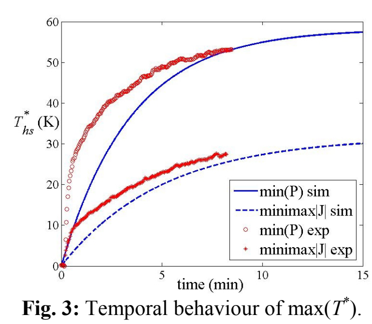

Fig. 3: Temporal behaviour of max(T^*).

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