

Minimum maximum temperature gradient coils: experimental analysis

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Introduction: Gradient coil operation suffers from overheating in portions of the coil where the windings are closely spaced, which may cause B_0 drift during an examination and even damage to the gradient coil. Recently, Poole et al. [1,2] and While et al. [3,4] proposed methods that spread the coil windings in these troublesome regions. In the latter the authors developed an analytical model for the spatial temperature distribution of a gradient coil with arbitrary geometry and thermal material properties and used the total square of the gradient of this distribution as a constraint in a relaxed fixed point iteration routine for redesigning the coil windings. Elsewhere this optimisation routine has been reworked to target the maximum coil temperature directly using sequential quadratic programming to provide gradient coils with up to 50% lower peak temperature (above ambient) when compared to standard minimum power coils, at no cost to coil performance. In the present work, a set of prototype coils were designed using this *minimaxT* method, built and tested along with an equivalent minimum power coil and a minimum maximum current density coil [2] for comparison.

Theoretical design: A cylindrical copper sheet of radius r_c , length $2L$ and thickness w was used to represent the gradient coil, which was embedded in a number of other cylindrical layers of different materials. The spatial temperature distribution at thermal equilibrium for this arrangement was simulated using the analytical method of While et al. [4,5]. This method solves a heat equation using Fourier series and includes the heat processes of Ohmic heating due to current density \mathbf{j} (A/m) in the copper layer, heat conduction across this layer, radial conduction through the other layers in the system and radial convection and radiation to a lossy environment. A standard minimum power coil was used as an initial guess in an iterative optimisation scheme for redesigning the coil to display minimum maximum temperature. The function *fminimax* from MATLAB's Optimisation Toolbox was used for this purpose and 128 Fourier modes were considered as free parameters. To preserve field linearity, the maximum excursion from the target field was constrained to be less than or equal to 5% at each iteration. The temperature distribution depends heavily on the chosen material properties and cooling mechanism for the system and hence these parameters also alter the final *minimaxT* coil solution. Since the coil layer was modelled as a single sheet, primary uncertainty lies with the effective thermal conductivity (assumed isotropic) of this layer, k_e , and also the convective heat transfer coefficients at the inner and outer surfaces, h_i and h_o , respectively. As such, four different *minimaxT* coils were designed representing a reasonable range of these parameters.

Experimental setup: Six prototype coils were constructed: one minimum power coil, four *minimaxT* coils and one *minimaxJ* coil [2]. The windings for each coil were etched from 0.15 mm flexible PCB with 35 μ m copper layers on either side. This dual layer arrangement avoided the necessity for return paths, which can act as heat sinks and therefore alter significantly the temperature distribution due to the coil. The PCBs were scaled to fit around the outside of an acrylic pipe of outer radius 70 mm (thickness 5 mm) with a coil length of 245 mm ($l/d=1.75$) and fastened using electrical tape with a matte finish. The drive current for each coil was chosen carefully to ensure that gradient strengths were matched between coils. A NEC F30 thermal imaging camera was used to take temperature measurements at 30 s intervals over a 15 min period once the coil systems had reached thermal equilibrium (after a conservative 2 hours).

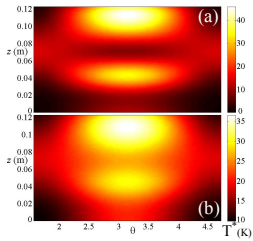


Fig. 1: Temp. distributions for min. power coil (one quadrant) with: (a) low thermal conductivity and high cooling, and (b) high cond. and low cooling.

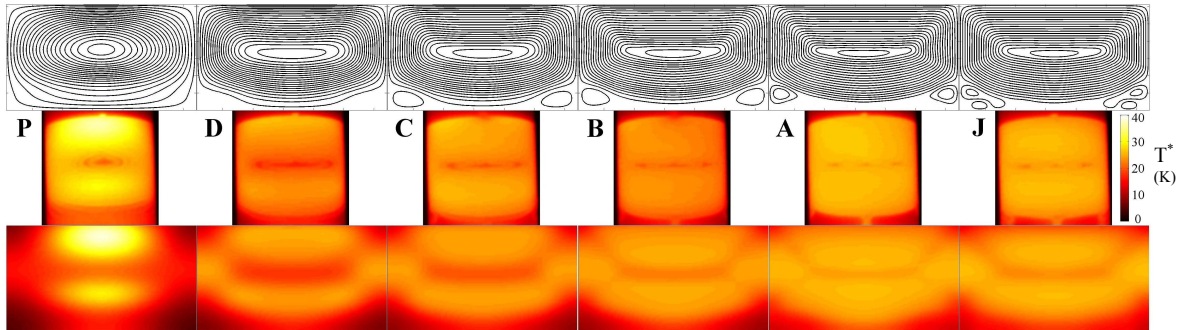


Fig. 2: (top) Coil windings (one quadrant) for the minimum power coil (P), the 4 *minimaxT* coils designed assuming different coil parameters (A-D), the *minimaxJ* coil (J); (middle) imaging data at thermal equilibrium; (bottom) simulated temperature distributions.

Results and discussion: Fig. 1 displays two different temperature distributions associated with one quadrant of the minimum power coil corresponding to the two extreme combinations of k_e , h_i and h_o . Note that for low k_e and high h_i and h_o , the temperature distribution displays distinct hot spots (Fig. 1(a)), whereas for high k_e and low h_i and h_o , the temperature distribution is much more diffuse (Fig. 1(b)). Fig. 2(top) display the coil windings for the minimum power coil (P), the four *minimaxT* coils (A-D), and the *minimaxJ* coil (J). In the extreme *minimaxT* cases, coil A (designed for low k_e , high h_i and h_o) displays an even spreading and distinct squaring of coil windings, whereas coil D (designed for high k_e , low h_i and h_o) displays a more rounded appearance with a “fish-eye” effect in the dense region of large extent. Indeed in the limit of zero thermal conductivity and infinite cooling, the *minimaxT* regime tends to *minimaxJ*, and in the opposite limit (infinite conductivity and zero cooling) it tends to minimum power. As such, the introduction of finite conductivity effectively regularises the problem and provides varying levels of “fish-eye” effect as demonstrated in Fig. 2. The thermal imaging data averaged over 15 min for each coil at thermal equilibrium is displayed in Fig. 2(middle) and maximum temperature (above ambient) is recorded in Table 1. Clearly the five *minimax* coils are superior to the minimum power coil; however, coils A, C, D and J cannot be distinguished due to an estimated experimental error of approximately 1K in each case. This demonstrates that the sensitivity of the solution is low with respect to the estimation of coil parameters such as effective thermal conductivity and, as such, only approximate values are required to generate useful *minimaxT* coils. Nevertheless, coil B was found to be significantly superior to the others and demonstrates that with careful estimation of coil parameters a truly optimum *minimaxT* coil can be obtained. Note that in reality, the best set of values for these coil parameters in this case is likely to lie somewhere between the two intermediate combinations of k_e , h_i and h_o . The simulated temperature distributions for each coil assuming one of these combinations are displayed in Fig. 2(bottom), which match qualitatively the experimental results, and this provides further confidence in the temperature distribution model [6]. In summary, the *minimaxT* design method was found to be useful for generating coil windings with improved thermal performance and reduced maximum temperature at little cost to coil performance.

References:

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