Optimisation of Flux Concentrator-Coil Design for Application in Magnetic Hyperthermia

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Abstract. This study investigates some key optimisation aspects of applicator coils with ferrite-based flux concentrators for magnetic hyperthermia treatment. We found that the enhancement of the magnetic field flux from the coil with the aid of flux concentrators comes at a cost of increased inductance – which demands lower capacitance counterparts in a high-frequency resonance LC circuit – and higher AC resistance, which generates unwanted Joules heating. Positioning the coil at the application end of the flux concentrator increases the magnetic field strength dramatically, whilst reducing inductance and AC resistance. Preliminary experiments indicate that the increased magnetic field strength from flux concentrators of higher aspect ratio saturates above a certain concentrator-to-coil length ratio of around 15. Using a high degree of perforation of the core results in negligible difference in magnetic field progression. By optimising the relative coil-to-concentrator dimensions, AC resistance can be limited as proximity effects resulting from ferrite concentrator and coil interaction are reduced. The latter two findings enable new opportunities to improve the cooling efficiency.

1. Introduction

With a myriad of different types and pathophysiology, cancer and its treatment remains one of the most challenging healthcare challenges in the world. It is therefore not surprising that a majority of past and current research efforts are focused on the discovery and development of viable alternatives to the status quo of cancer treatment – namely surgery, radiotherapy or chemotherapy (or a combination of them). Many of the most promising new therapeutic technologies use magnetic nanoparticles for diagnostic purposes, for instance in contrast-enhanced magnetic resonance imaging (MRI), and/or for therapeutic use, by exploiting their unique properties to deliver remedial payloads (e.g. drugs, genes) or by delivering the therapy themselves, i.e. hyperthermia, the topic of this work. For a review on magnetic nanoparticles in medical applications, please refer to [1].

Only recently, magnetic hyperthermia has found its way to the hospital, with the first approved treatment centre at the Charité-Universitätsmedizin Berlin established and offering an alternative therapy to brain tumour patients (www.magforce.com).

During a typical magnetic hyperthermia therapy nanometre-sized magnetic particles are initially administered to the tumour site. A powerful alternating magnetic field is then used to trigger relaxation mechanisms in the magnetic nanoparticles, thereby releasing a possibly lethal dose of heat into the target volume [2]. Compared to thermal ablation, a process in which cells are necrotised at temperatures up to 56 °C, hyperthermia heat ranges only from 42-45 °C, where tumour cells are more...
sensitive to heat than healthy tissue and can be forced to a programmed cell death, known as apoptosis [3].

Whereas many magnetic hyperthermia systems are designed to treat tumours located deep inside the body, our objective is to develop an applicator for the treatment of superficial targets, i.e. melanoma, and breast cancer at most. As such, we estimate that only a penetration depth of 1-3 cm for the magnetic field is needed, and based on requirements demanded by recent studies [4] we set a condition of achieving a frequency-field product of 8 MHzOe to heat gold-plated iron shots (1 mm in diameter) to 42.5 °C. In other words, for 500 kHz frequency, a field of 16 Oe is needed. In an ideal resonant circuit, frequency \( f \) is related to capacitance \( C \) and inductance \( L \) as \( f = 1/(2\pi\sqrt{LC}) \). Therefore, to achieve a certain frequency, increasing the inductance implies lowering the capacitance and vice versa. For high-current circuits (several 10s of Amps), however, only few manufacturers\(^1\) offer high-power, high-frequency and low-valued capacitors at substantially higher prices. Therefore, we regarded better designed coils to have lower inductances.

Currently, during our preliminary phase, we employed a current of only 10 A, yet we anticipate to increase the input to about 20 A, if heat loss allows. For our purposes, we have already designed and built a control circuit using a complex programmable logic device (CPLD), a programmable control chip, to drive an LC resonant tank.

Additional to an LC tank, we propose the use of ferrite cores as flux concentrators in order to amplify the magnetic field. One downside of using cores is that various parameters of the coil configuration are shifted (e.g. inductance \( L \), series resistance \( R_s \)), ultimately requiring new design considerations, such as the adjustment of the inductor-capacitor values in a given LC circuit and foremost the additional heat generation due to increased \( R_s \). Heat is not only generated in the coil conductor but also in the ferrite core in high-frequency applications. In the case of our core material (see below for specifications), however, the core loss data provided by the manufacturer suggests at a 500 kHz frequency point, negligibly small heat is dissipated from the core at the above mentioned target field.

In order to limit heat generation for an air-cooled system, we hoped to achieve a power dissipation of ~20 W maximum. According to Joule’s Law, this means that for a current input of 10 A, an \( R_s \) of around 0.2 \( \Omega \) or less could only be tolerated, which was around the noise level of our LCR meter. This challenge was exacerbated by skin and proximity effects from high frequencies, adjacent windings, the inclusion and proximity of the flux concentrator and the latter obstructing the airflow through the coil, respectively.

Here, it should be noted that the ferrite cores did not behave as ideal soft magnetic materials because they were used at near-saturation conditions, where magnetic domain movements essentially determine the dependence of the magnetic field on the current.

Therefore our studies are aimed at providing some guidelines on how to achieve design improvements for practical applications and non-ideal situations. This study is sectioned into four experiments: (i) the coil position with respect to the concentrator was tested, (ii) the relevance of concentrator aspect ratio was investigated, (iii) the ferrite flux concentrator was perforated and the different configurations were obtained and (iv) the dimensions of the concentrator relative to the coil were varied.

2. Experimental

\(^1\) E.g. www.celem.com
To investigate potential design improvements, we constructed a number of different coils. All coils used 1.25 mm$^2$ (copper cross-section) wire with total OD=3 mm including insulation. The flux concentrator consisted of a collection of 120 mm-long, 5x5 mm square-faced ferrite core rods (PC-40, TDK Corporation), as shown in figure 1. The coil specifications for each section are summarised in table 1, whereby a (round) solenoid as well as several square-faced coils were employed.

Magnetic field progression was measured using a gaussmeter (LakeShore® 455 DSP Gaussmeter), where both AC and DC values gave similar trends at a current input of 10 A. Only DC values are therefore presented in this work. Inductance and resistance were measured using an LCR meter (Hioki® LCR HiTESTER 3532-50). The former was constant across a frequency ranging from 100 kHz to 1 MHz and only relative values are provided here. Since the AC resistance data was recorded at around the noise floor of the LCR meter, the data were re-fitted with an averaging function for the reader.

| Experiment        | Coil Type | No. of turns | Pitch (mm) | Side length or Ø (mm) |
|-------------------|-----------|--------------|------------|-----------------------|
| Coil Position     | Round     | 6            | 3          | 30                    |
| Aspect Ratio      | Square    | 7            | 3          | 35                    |
| Perforation       | Square    | 36           | 3          | 35                    |
| Rel. Dimensions  | Square    | 12           | 10         | 35                    |

Table 1 Specifications of the coils used in the experiments.

3. Results & discussion

3.1. Coil positioning

In this setup, we altered the position of the coil with respect to a given flux concentrator consisting of 4 (= 2x2) ferrite rods. The progression of the magnetic field from the centre of the face of the flux concentrator is shown in figure 2(a). We discovered that positioning of the coil at the application end (in our experiment, that is the gaussmeter probe), enhanced the magnetic field by ca. 80% at 10 mm and 40% at 30 mm compared to a coil located in the middle of, or around the entire length of the core and even higher compared to a coil positioned at the opposite end.

This adjustment also reduced inductance considerably as compared to a central positioning. Using a 6-turn coil, we could indeed achieve 20 G at 10 mm, which satisfies our minimum requirement.
A coil with an identical nominal conductor length but wound at a pitch that covered the entire concentrator conserved flux leakage across the length of the concentrator; however, the number of turns per length was drastically reduced and resulted in substantially lower magnetic fields strength.

Resistances of the different configurations given in figure 3(b) showed that $R_S$ was hardly affected by changing the coil positioning up to our target frequencies, unless wound loosely. For higher frequencies, a central positioning tended to increase more rapidly than other configurations.

3.2. Aspect Ratio

The aspect ratio in our case was defined as the ratio between the length of the flux concentrator and side length of the total ferrite face $\text{AR} = \frac{L_{\text{ferrite}}}{a_{\text{ferrite}}}$. Maintaining all other parameters constant, flux concentrators of varying lengths were inserted.

The data suggested that no significant improvement in magnetic field strength was seen above a certain aspect ratio – in our case above $\text{AR}=6.2$. This could be linked to the relative lengths of coil and concentrator, i.e. $\frac{L_{\text{ferrite}}}{L_{\text{coil}}}$. If we plot the magnetic field strength at 10 mm against $\frac{L_{\text{ferrite}}}{L_{\text{coil}}}$ (not shown) we find that the saturation occurs around a value of $\frac{L_{\text{ferrite}}}{L_{\text{coil}}}=15$, meaning that above a flux concentrator length that is 15 times longer than the coil length, no significant performance increase is observed.
Unsurprisingly, using shorter flux concentrators reduced the inductance and AC resistance substantially. The trade-off between loss of field strength (ca. 20% between AR=2.8 and AR above) and reduction of inductance (ca. 12%) and $R_S$ (ca. 25%) meant that depending on the importance of a parameter of choice the design could be optimised.

With one turn more than the previous, this configuration provided a higher reach of our target field.

### 3.3. Concentrator perforation

In this experiment, we used a 36-turn, tightly-wound coil (hence higher inductance and AC resistance) to raise the measurement values above the noise floor. We arranged the ferrite rods in a number of configurations to explore the effects of interstitial gaps on the overall performance, as shown in figure 4. Perforation increased the effective aspect ratio and reduced the demagnetization effect, and therefore better outcome was expected for an *ideal* soft magnetic material.

![Figure 3](image-url) For a set coil, the aspect ratio of the flux concentrator was changed to compare performance differences. Magnetic field (a) and AC resistance (b) for ferrite cores ranging from 2.8 to 12.8 in aspect ratio.
We discovered that the magnetic field was hardly affected, neither by the arrangement of the configuration nor by number of rods used. The exception occurs for only a single configuration (centre 2x2), which showed a significantly lower L and Rs, whilst delivering similar field progression as others. Note that this result was not dependent on the number of rods, as 4 rods placed on the corners gave a different result to 4 rods arranged in a 2x2 configuration. Although not with the 2x2 configuration, we could indeed achieve our target magnetic field at 30 mm with the other configurations.

3.4. Flux concentrator dimensions
The previous results prompted us to investigate the relationship between flux concentrator and coil dimensions. As exemplified in figure 5, for a given coil the concentrator dimensions were varied. Furthermore, for the 4x4 and 3x3 configurations, we also removed the centre rod(s).

We found that the difference in magnetic field strength between larger and smaller concentrators increased with distance between core and coil (figure 5(a)). In other words, whilst a large 4x4 configuration delivered an 8% higher magnetic field at 10 mm than the 2x2, it outperformed the latter by ca. 35% at 30 mm. The trade-off was rewarded with a 50% lower inductance and a lower trend in Rs (figure 7(b)). It is assumed that this was due to a lower proximity effect in the conductor as concentrator-coil distance was increased.
The most astonishing results, however, were observed when comparing a 4x4 configuration with its counterpart with its central rods removed. All parameters between them can be regarded as identical. Thus, by inserting a hole (or possibly several) in a solid ferrite flux concentrator, the same qualitative performance were produced whilst enabling an opportunity for better cooling through the core of the coil.

4. Optimised configuration and conclusions

On the basis of these findings and referring to the target frequency-field product of 8MHzOe, we expect a 10-turn coil with a current of 15 A and a 'holed' 3x3 flux concentrator to be sufficient to meet the demands of our suggested therapy.

During this preliminary design phase, we were indeed able to achieve the required field strength at our minimum target distance only, partly due to a current of only 10 A. Furthermore, our “effective permeability” (i.e. the factor by which the magnetic field strength of an air coil could be improved by inserting the ferrite cores) was limited to ca. 10 or less, which indicated that the ferrite cores did not exhibit ideal soft magnetic properties when the relatively strong current (10 A) was applied. However, we found that there are indeed several factors that may be considered to optimise an applicator. (1) Using the coil near the application end of the ferrite flux concentrator increased the magnetic field progression as well as lower the inductance. (2) A concentrator length of above 15 times the coil length did not increase the performance. (3) Using perforated flux concentrators had little influence on the magnetic field strength, but lowered inductance and resistance values. (4) Using a flux concentrator located centrally and with smaller dimensions (side length or diameter) resulted in

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Figure 5 Magnetic field (a) and AC resistance (b) for ferrite cores with varying sizes, altering the space between the core and the coil.

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a reduction in AC resistance. Perforating the centre of the flux concentrator, which had no detrimental effect on magnetic field strength, would also facilitate cooling.

Our next objectives include the measurement of real power dissipation from the inductor and actual power requirements for different flux concentrator configurations. Additionally, magnetic flux simulations are currently under way to confirm our measurements numerically and to explore more complex coil/concentrator designs.

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