The Design of a Half-bridge Series-resonant Type Heating System for Magnetic Nanoparticle Thermotherapy
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Abstract — Application of magnetic materials for hyperthermia of biological tissue has been known, in principle, for more than four decades. Many empirical works were done in order to confirm a therapeutic effect on several types of tumors by performing experiments with animals or using cancerous cell cultures. The main idea of magnetic nanoparticle (MNP) thermotherapy is to utilize 7- to 50-nm diameter of ferric oxide (Fe$_3$O$_4$) particles which are heated up to 42°C under AC magnetic field for cancer therapy applications. In order to achieve the goal of killing cancer cells using the AC magnetic field, we designed a heating system to generate magnetic field which can be focused and frequency adjustable. This study adopts the half-bridge series-resonant type circuit as the core scheme of the heating system, and utilizes the frequency-adjustable design to conduct the heating experiment. The experiment results show that the designed coil and the heating system can warm up the magnetic nanoparticle 6°C in 32 minutes.

1. INTRODUCTION
Electromagnetic inducing of heat has been extensively studied for the treatment of hyperthermia, wherein case deposited magnetic particles are used to locally heat human tissues. The basic idea of hyperthermia is raising the tissue temperature up to between 41.5 and 46°C to kill malignant cells while preserving normal cells [1]. Many empirical works were done in order to confirm the therapeutic effect on several types of tumors by performing experiments with animals [2] or using cancerous cell cultures, and poor AC magnetic field parameters [3]. At least two full-sized human prototypes have been built based on magnetic fluid hyperthermia (MFH) and used shortly for the first clinical trials of hyperthermia [3]. But, these systems are too bulky and with poor heating efficiency. Therefore, we want to develop a more compact, stable and efficient heating applicator. Our research is focused on heating system design and the improvement of applicator [4, 5].

2. SYSTEMATIC CIRCUIT STRUCTURE
The circuit diagram of the heating system is shown in Fig. 1, which includes a rectification circuit, a converter circuit, gates driver, a half-bridge MOSFET inverter and an applicator. The half-bridge series-resonance circuit [6] basically has two bi-directional switches of power MOSFET (Q1 and Q2) and a resonant circuit. Each power switch (S1 or S2) is composed of a switch of MOSFET (Q1 or Q2), as shown in Fig. 2. According to the combined form of the MOSFETs and the resonant circuit, it can commonly be classified into the series resonant topology, parallel resonant topology, and a combination series-parallel resonant topology. The power MOSFET is focused on turn-on resistance, reducing conduction losses, operating junction temperatures, and switching speeds. This proposed circuit is adopted to avoid introducing any DC voltage upon the applicator during operation. The power MOSFET switches, Q1 and Q2, of the HBSR inverter are gated by two complementary signals, $v_{gs1}$ and $v_{gs2}$, respectively. Each switch (S1 or S2) is composed of a switch of power MOSFET Q1 (Q2) and its intrinsic anti-parallel diode D1 (D2). To prevent cross condition, the waveforms of $v_{gs1}$ and $v_{gs2}$ should be non-overlapping and have a short dead time. AC voltage supply is given in input voltage 110 V\textsubscript{rms} and output voltage. By symmetrically driving two power MOSFET switches, the output of the HBSR inverter is a sine-wave voltage with a DC term of $V_{dc}/2$ on the applicator circuit. Thus, a DC-blocking capacitor ($C_{S1}$ and $C_{S2}$) must be used for blocking the DC term of the square-wave. On the other hand, the HBSR inverter outputs a square-wave voltage without any DC term on the applicator circuit. Hence, there is no DC component across the applicator to increase the current during resonant [7, 8].

3. COIL MODELING AND HEATING SYSTEM
The applicator consisted of two parts, wire coil and ferrite core. Although the structure of the electromagnetic coil seems quite simple, its high frequency and high current mechanism are very
complicated. Fortunately, when the applicator operated in high frequency, it has been demonstrated to be approximately an open circuit, and the coil characteristic is not sensitive as verified from the impedance analyzer (Agilent 4294 A). Fig. 3 shows the comparison of coil models from measurement and simulation (impedance and phase). The operation characteristics of the high-frequency heating system can be calculated by using the applicator model shown in Fig. 4. The measured parameter values of the coil model are listed in Table 1. The E-type geometry structure of the applicator and the simulated distribution of magnetic field are shown in Figs. 5 and 6. The MNP heating system is shown in Fig. 7.
4. EXPERIMENT RESULTS AND DISCUSSION

The induced electromagnetic heating effect in magnetic materials is mainly attributed to three physical phenomena, namely, hysteresis, eddy current, and Néel or Brownian relaxation losses. The total power loss in a conductor media is [9]:

\[
P_{\text{total}} = \left( \beta_h \mu + \beta_e \frac{\mu^2 f}{\rho} + \beta_{nb} \frac{2\pi f \tau}{1+(2\pi f \tau)^2} \right) f H^2,
\]

where \(\beta_h\), \(\beta_e\) and \(\beta_{nb}\) are the geometry constant coefficients of hysteresis, eddy current, and Néel or Brownian relaxation, \(\mu\) is the permeability of the magnetic material, \(H\) is the amplitude of the applied AC magnetic field, \(\rho\) is electrical resistivity, \(\tau\) is relaxation time and is exponentially size dependent. However, heating of MNP is inherently due to hysteresis losses and Brownian relaxation.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Concentration (Fe/mL)</th>
<th>Amount (mL)</th>
<th>Temperature Difference ((\Delta T/\Delta t))</th>
<th>SAR values (W/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.02887</td>
<td>Fe(_3)O(_4) (2.0 mL)</td>
<td>4.9E-3</td>
<td>0.653</td>
</tr>
<tr>
<td>B</td>
<td>0.0144</td>
<td>Fe(_3)O(_4) (1.0 mL) + Water (1.0 mL)</td>
<td>2.6E-3</td>
<td>0.694</td>
</tr>
<tr>
<td>C</td>
<td>0.02887</td>
<td>Fe(_3)O(_4) (1.5 mL)</td>
<td>5.2E-3</td>
<td>0.693</td>
</tr>
<tr>
<td>D</td>
<td>0.02887</td>
<td>Fe(_3)O(_4) (1.5 mL)</td>
<td>5.1E-3</td>
<td>0.679</td>
</tr>
<tr>
<td>E</td>
<td>0.02887</td>
<td>Fe(_3)O(_4) (1.5 mL)</td>
<td>4.4E-3</td>
<td>0.586</td>
</tr>
</tbody>
</table>
losses [10, 11]. In fact, the experiment results of many studies revealed that the heating power loss is affected by the strength of magnetic field and the characters of the material, such as particle size, size variation, and magnetization saturation [12]:

\[
SAR = C \frac{\Delta T}{\Delta t} \frac{1}{m_{Fe}},
\]

where \( C \) is the specific heat of sample, \( \frac{\Delta T}{\Delta t} \) is temperature gradient. The experimental values of SARs for five different cases are shown in Table 2.

In experiments A and B (Fig. 8), the results show absolute heating temperature for different \( Fe_3O_4 \) concentration. Furthermore, the heating effects on nanoparticle (\( Fe_3O_4 \)) are mainly attributed to three physical phenomena, as indicated in (1). The heating curves, C, D, and E, for different initial temperatures are shown in Fig. 9. The results show similar curves which agree with the expected physical characteristics.

![Figure 8](image1.png)  
**Figure 8:** Experimental results for absolute heating temperature at different concentration.

![Figure 9](image2.png)  
**Figure 9:** Experimental results for absolute heating temperature at different initial temperature.

5. CONCLUSION

In this study, we have succeeded in using the half-bridge resonant methods with coil design using Litz wire to heat iron powder and magnetic nanoparticle. The results show that under different background temperature all the samples can be heated up to 42°C in AC magnetic field. There is an absolute temperature increased about 6°C in 32 minutes. We have achieved a substantial step to the final goal of killing cancer cells using the AC magnetic field and have attained the expected heating effect for the study.

ACKNOWLEDGMENT

This research was supported by the grant from National Science Council, Taiwan (NSC 95-2221-E-006-016). Also, this work made use of Shared Facilities supported by the Program of Top 100 Universities Advancement, Ministry of Education, Taiwan.

REFERENCES


