Contract No:

This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy (DOE) Office of Environmental Management (EM).

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Magnetic Induced Heating of Gold-Iron Oxide Nanoparticles

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***Abstract*—This study investigates the heating characteristics of aqueous solutions of nanoparticles (NPs) through a magnetically induced field. Through simulation and experimental studies, key parameters that affect the temperature profiles of magnetic nanoparticles (MNPs) are identified. Specifically, the influence of magnetic field strength, MNPs concentration, MNPs composition, and coil size was explored as a way to understand the correlation between the NPs structure and the magnetic induced heating process.**

I. Introduction

There is a growing interest in radio frequency electromagnetic (RF-EM) heating of NPs for biomedical applications such as separation of biomolecules [1], controlled drug release [1-2], and tumor ablation for cancer therapy [3]. Several studies have reported the use of NPs in RF-EM hyperthermia for cancer therapy or drug release treatments [1-3] as NPs could enter the body without harm. RF-EM energy then induces localized temperature gradients in the NPs, effectively killing the cancer cells [2] or releasing drugs to treat affected areas [1]. For hyperthermia therapy, temperatures of 41˚C – 46˚C were reported [2].

Magnetic field RF heating is based on hysteresis loss, Néel relaxation, and Brownian relaxation. Energy is transferred to MNPs as heat [4]. The benefit of this approach is the ability to remotely generate heat.

This paper focuses on magnetic induced heating of aqueous solutions of NPs. The research presented in this paper evaluates the feasibility of using an alternating magnetic field (AMF) to heat aqueous solutions of Fe_2O_3 and Fe_2O_3-Au MNPs. The heating effects as function of time, NP composition and concentration are delineated.

II. Experimental Procedures

A. Nanoparticle Synthesis

Fe_2O_3 NPs (50 nm) were purchased from Sigma-Aldrich and used to synthesize multifunctional magnetic-plasmonic NPs (Fe_2O_3-Au). To prepare Fe_2O_3-Au bimetallic nanostructures, gold was reduced in the presence of iron oxide nanoparticles using the Turkevich method [5]. Briefly, 2.5 nmoles of Fe_2O_3 and 1 mL of 1% trisodium citrate in 10 mL diH_2O was boiled before 250 nmoles of $HAuCl_4$ was added. Once the solution turned ruby red, it was cooled and magnetically purified three times and re-suspended in water.

B. Magnetically Induced Heating

A magnetic hyperthermia system with a 6 turn coil (17.5 mm radius and 47.5 mm height) was purchased from MSI Automation, Inc. Alternating magnetic fields at 425 kHz were generated by controlling the power to the coil.

Magnetically induced heating experiments were conducted on aqueous solutions of Fe_2O_3 and Fe_2O_3-Au MNPs. A Neoptix fiber optic temperature probe was used to monitor the temperature gradients in the solution. The MNPs were then placed inside the center of the coil of the magnetic hyperthermia system (Power = 80%). Theoretical simulations and mathematical calculations were performed using electromagnetic field simulation software called Ansys Maxwell.

III. Results and Discussions

Multifunctional MNPs were heated in the magnetic hyperthermia system as shown in Fig. 1.

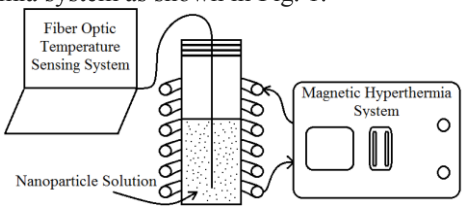


Fig. 1. Magnetic heating experimental design.

The gold NPs deposited onto the Fe_2O_3 NPs measured 19 nm in diameter as shown on the scanning electron microscope (SEM) image in Fig. 2. The SEM results show that the surface decoration with Au NPs does not change the initial morphology of the spherical Fe_2O_3 support. Also, the Fe_2O_3 NPs vary in size, but the Au NPs do not aggregate on the surface of either the smaller or larger Fe_2O_3 NPs resulting in a random distribution of Au on the surface. The Au NPs also remain attached to the surface of the Fe_2O_3 even after cycles of magnetic purification and dispersion in water.

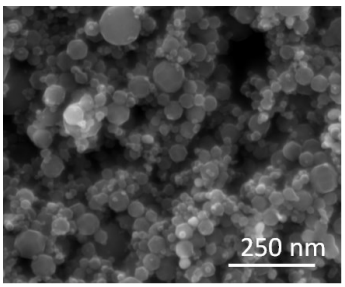
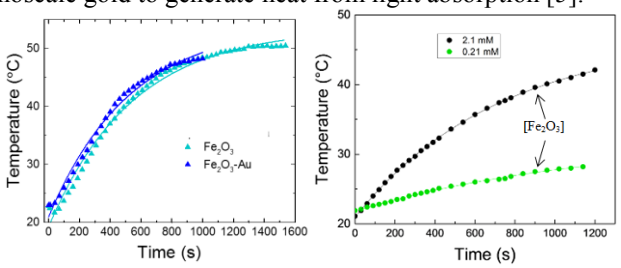


Fig. 2. SEM for Fe_2O_3-Au NPs.

The temperature profiles generated as function of NP composition (Fig. 3a) and concentration (Fig. 3b) are shown below. The temperature profile follows the same trend on the support and Au decorated support suggesting that the presence of Au does not impact the temperature gradients. This also suggests that the heat generated in the Au decorated support is due to magnetic heating rather than eddy currents. These results demonstrate the ability to construct NPs that exhibit both magnetic and plasmonic properties due to the ability of nanoscale gold to generate heat from light absorption [5].



(a) (b)

Fig. 3 Temperature dependence on NP parameters. (a) NP composition (b) NP concentration.

The temperature gradients are strongly dependent on nanoparticle concentration (Fig. 3b). At 2.1 mM of Fe_2O_3, the ΔT is four times larger than that of the 0.21 mM concentration of Fe_2O_3. Each individual magnetic NP is expected to be responsive to the AMF. As a result, each individual particle generates heat. The actual temperature rise measured is due to the overall summative contribution of each individual nanoparticle exposed to the magnetic field.

Simulation studies conducted with Ansys Maxwell were used to simulate the experimental coil and examine the intensity of the magnetic field inside the coil. At 80% power, the current generated within the coil was 17 amps. This corresponded to a maximum magnetic flux density (B_{max}) of 2.7 mT at the center of the coil using (1).

$$B_{max} = \mu_0 nI \tag{1}$$

where μ_0 is the permeability of free space, n is the number of turns per unit length (N/l), and I is the current through the coil [6]. Simulation results are shown in Fig. 4.

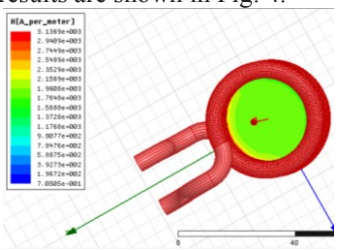


Fig. 4. Magnetic field strength at the center of the coil.

The simulation studies reveal that the magnetic field strength at the center of the coil is about 1760 A/m. This corresponds to a magnetic flux density of 2.2 mT as calculated based on $B = \mu_0 H$.

Theoretical calculations were also performed and compared with the simulation experiments to evaluate the effect of coil geometries on the magnetic flux density. Based on the Biot-Savart law [6], the magnetic field at the axial center of the coil with respect to the distance from the center along the length of the coil, l, can be calculated using (2).

$$B = \frac{B_{max}}{2}\left[\frac{\left(\frac{l}{2}\right)-z}{\sqrt{(z-l/2)^2+r^2}} + \frac{\left(\frac{l}{2}\right)+z}{\sqrt{(z+l/2)^2+r^2}}\right] \tag{2}$$

where B_{max} is the maximum flux density from (1), l is the coil length, r is the radius of the coil, and z is the distance from the center along the length of the coil. The calculated magnetic flux density is 2.17 mT at the center of the coil (z = 0 m). This confirms the simulated result of 2.2 mT. When compared with the experimental data, these simulation results describe the magnetic field strength required to raise the temperature of aqueous solutions of Fe_2O_3 and Fe_2O_3-Au MNPs to 50 ºC.

From (2), the main inhibitor of the magnetic flux density, B, reaching its maximum value, B_{max}, is the length of the coil and the radius of the coil. A radius twice as large (r = 35 mm) as the radius used in the simulation (leaving all other variables constant) would result in a magnetic flux density of 1.52 mT. This shows that a stronger magnetic field can be generated by using a smaller coil radius.

This study demonstrates that Au decoration on Fe_2O_3 support did not negatively impact the heat response of the aqueous solutions. Conversely, an increase in NP concentration had a positive impact on the heat response of NP solutions. Tunable temperature profiles can be achieved by controlling NP concentration, magnetic field strength, and coil geometries.

ACKNOWLEDGMENT

Financial support for this work was provided by the Department of Energy (DOE) and the Laboratory Directed Research and Development (LDRD) Strategic Initiative Program at the Savannah River National Laboratory (SRNL).

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