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A Versatile AMF Platform for Magnetic Hyperthermia Characterization Demonstrated with Pristine and Hybrid Magnetite Nanoparticles

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Abstract

In this work, we present a versatile hyperthermia platform enabling reproducible temperature–time measurements and systematic characterization of field-dependent heating behavior. The capability of the system is demonstrated by investigating the hyperthermia performance of pristine and hybrid magnetite nanoparticles through specific absorption rate (SAR). While pristine particles exhibit moderate SAR values, hybrid systems maintain effective magnetic heating despite reduced magnetic content. Efficient heating at low magnetic loadings indicates that hybridization does not compromise hyperthermia performance and supports the development of multifunctional nanoparticle systems.

I. Introduction

Magnetic nanoparticle mediated hyperthermia is a promising minimally invasive therapeutic approach based on localized heat generation under an alternating magnetic field (AMF). Quantitative evaluation of heating efficiency relies on determining the SAR from temperature–time measurements under well-defined excitation conditions. Reliable and systematic particle characterization therefore requires controlled magnetic field parameters and stable measurement environments. To meet these requirements, we developed a versatile magnetic hyperthermia platform enabling flexible and reproducible control of magnetic excitation conditions. The system supports systematic investigation of field-dependent heating behavior and magnetic relaxation processes.

In this work, we demonstrate the applicability of the platform by characterizing the hyperthermia performance of pristine and hybrid magnetite-based nanoparticles designed for multifunctional applications [1, 2].

II. Materials and Methods

Four magnetic nanoparticle systems were investigated using the AMF platform.

II.I. Hybrid Nanoparticle Systems

Pristine magnetite nanoparticles stabilized with triethanolamine (TEA) were used as the reference material, while a polymer-coated variant (PEI) was obtained by surface modification with polyethylenimine. Two hybrid systems incorporating gadolinium-based phases were also studied: (HB1) Mag@Gd_2O_3 and (HB2) Mag@$GdBO_3$, consisting of magnetite cores combined with gadolinium oxide or borate components.

II.II. Nanoparticle Characterization using the AMF Platform

The custom-developed versatile AMF platform consists of a water-cooled induction coil powered by a high-frequency power source. The platform is capable of generating alternating magnetic fields from 100 kHz to 700 kHz with amplitudes up to 40 mT and axial homogeneity of 96.3% over a 30 mm span and 73.5% over a 60 mm span.The system provides stable operation over 30 minutes and supports advanced excitation schemes, including superimposed DC bias fields to enable localized heating and interleaved DC-AC field sequences for particle alignment. All measurements were performed at a magnetic field amplitude of 15 mT and a frequency of 302.4 kHz. Aqueous dispersions (50 µL water) of the nanoparticles (20 mg) were placed at the center of the coil, and the temperature was monitored with fiber optic fibers. The initial linear region of each heating curve was used to determine the temperature rise rate ($\Delta T/\Delta t$) for SAR calculations. SAR values were calculated considering only the heat capacities of water and magnetite to enable consistent comparison among samples.

III. Results and Discussion

Figure 1 shows the heating performance of the nanoparticle dispersions. All samples exhibit a monotonic increase in temperature upon field application, with clearly different heating rates depending on composition. Among the pristine magnetic nanoparticles, TEA exhibits a SAR value of 0.62 W/g, while PEI shows a higher SAR of 1.46 W/g. The enhanced heating efficiency of PEI can be attributed to differences in surface coating and aggregation state, which may influence magnetic relaxation processes under the applied field. For the hybrid systems, distinct behaviors are observed. HIB1 displays a measurable SAR value of 0.82 W/g despite its reduced magnetic content, indicating that the magnetic cores remain responsive following hybridization. In contrast, HIB2 exhibits a significantly higher SAR value of 7.5 W/g, even though it contains a very low fraction of magnetite. This apparent enhancement arises from normalization of the absorbed power to a small magnetic mass, highlighting that efficient magnetic heating can be achieved at low magnetic loadings. Overall, the results demonstrate that the hybridization strategy does not suppress magnetic heating capability. While absolute SAR values are influenced by magnetic content and normalization assumptions, the relative trends confirm the preservation of hyperthermia performance in the hybrid nanoparticle systems.

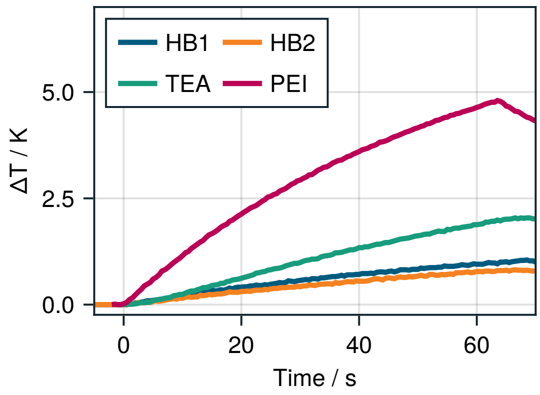

Figure 1: Temperature curves of the nanoparticle dispersions under an alternating magnetic field.

IV. Conclusion

SAR values show that hybridization preserves the magnetic heating capability of magnetite nanoparticles. Despite reduced magnetic content, the hybrid systems exhibit measurable and in some cases enhanced SAR values, supporting their suitability for multifunctional hyperthermia applications.The presented AMF platform enables reliable and systematic characterization of such nanoparticle systems under controlled excitation conditions.

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Author's statement

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