

Simulation and experimental research on model parameter in a magnetic nanoparticle thermometer

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Abstract—Magnetic nano-temperature measurement is a new type of non-contact temperature measurement method, which is expected to overcome the technical bottleneck of the current internal temperature of the tumor in the tumor hyperthermia. In view of the current low measurement accuracy of magnetic nanometer temperature measurement, this paper studies the system and model parameters, and uses the low frequency triangular wave as the excitation magnetic field to analyze the influence of model and system parameters (particle size and excitation magnetic field strength) on temperature measurement accuracy. And optimize and improve the related system and model parameters. The results show that as the effective particle size of the magnetic nanoparticles increases, the average effective magnetic moment of the sample increases, and the magnetic nanometer temperature measurement accuracy increases. For the smaller diameter magnetic nanoparticles, as the applied excitation magnetic field increases, the accuracy gradually increases. After selecting a certain magnetic nanoparticles, the optimal excitation magnetic field size can be found to maximize the temperature measurement accuracy. The magnetic nanometer temperature measurement method achieves higher temperature measurement accuracy, enabling it to be applied to higher temperature measurement accuracy requirements.

Keywords—Magnetic nanoparticles, Parameter optimization, Temperature measurement, Langevin's equation

I. INTRODUCTION

Tumor hyperthermia is a new "green" therapy after traditional surgical, radiotherapy and chemotherapy. The principle is to use physical energy to heat the whole body or part of the human body, so that the temperature of the tumor tissue rises to the effective treatment temperature, and maintains a certain time. It uses the difference in temperature tolerance between normal tissues and tumor cells to achieve the therapeutic purpose which is not only inhibit tumor cells without damaging normal tissues [1]. Therefore, temperature plays a crucial role during tumor hyperthermia. It directly affect the final treatment effect.

The temperature measurement methods are mainly divided into two categories: invasive and non-invasive temperature measurement methods in tumor hyperthermia. At present, invasive temperature measurement methods mainly include the following methods: temperature measurement uses a thermocouple as a sensor, temperature measurement uses a carbon high-resistance wire, and using a thermistor in clinical practice. However, these temperature measurement methods must be placed inside the human body tissue for temperature measurement. There are several disadvantages: First, the probe

volume and human tissue structure limit the temperature measurement, the intrusive temperature measurement can detect number of temperature points, which is very limited. Temperature data at a limited number of points does not accurately reflect complete temperature information inside the body tissue. Second, the temperature probe will interfere with the heat dissipation of the tissue and have an unpredictable effect on the treatment effect. Third, due to the measurement limitations of the temperature principle, the probe must be placed inside the human body. This process may increase the risk of tissue infection and the risk of treatment [2]. Non-invasive temperature measurement methods can make up for the insufficiency of intrusive temperature measurement. Magnetic nanometer temperature measurement is a new type of non-immersion temperature measurement technology. The magnetized magnetic particles exhibit magnetic sensitivity under the action of an external magnetic field, and the temperature information is inverted by the magnetization response of the magnetic nanoparticles, thus this can realize high-precision non-invasive temperature measurement. Magnetic nanometer temperature measurement is expected to overcome the technical bottleneck in the tumor hyperthermia where the internal temperature of the body cannot be measured. It provides effective temperature feedback for the tumor hyperthermia process to enhance the thermotherapy effect.

In 2012, Zhong Jing et al. established a theoretical model based on the first-order Langevin's equation [3-4], and used SQUID VSM to measure the magnetization curve under different DC excitation magnetic fields, and realized the temperature measurement by inversion calculation method [5]. At the same time, the theoretical model of temperature measurement was optimized and achieved higher precision [6]. However, temperature measurement methods under different DC excitation magnetic fields do not have good real-time and operability of temperature measurement. Under the low-frequency AC excitation magnetic field, the magnetization has time-varying based on the Langevin's function. Therefore, a temperature measurement method is proposed under a low-frequency and time-varying excitation magnetic field. At present, there are two methods for measuring the temperature under low-frequency and time-varying magnetic field. One is to obtain the magnetization curve in real time under the excitation of the triangular wave magnetic field, and the temperature is measured by the discrete magnetization curve. The second is to use the characteristic of the harmonic amplitude of the AC magnetization excited by the sine wave magnetic field to measure the temperature. The harmonic amplitude have temperature sensitivity [7]. The temperature

measurement accuracy is allowed to vary within 1 degree for tumor magnetic hyperthermia, and the existing magnetic nano-temperature measurement method can well achieve the accuracy. And in an environment where temperature measurement accuracy is higher, such as the study of temperature changes in biological tissue cells, the current technology for exploring this temperature change is mainly achieved by optical measurement methods [8]. Although optical measurement methods can achieve relatively high measurement accuracy, there is no way to measure the on-line temperature of deep tissue in living organisms. Magnetic nano-temperature measurements can take advantage of their magnetically transparent properties and it is expected to be used for on-line temperature measurements in deep tissue cells. The parameters affect the measurement accuracy of the temperature in the temperature measurement model. Therefore, optimizing the parameters helps to further improve the measurement accuracy.

The temperature measurement uses the harmonic amplitude, which is required to have a higher signal-to-noise ratio under the excitation of the sinusoidal magnetic field. But it do not need high in the system and is easy to implement under the excitation of the triangular wave magnetic field. Therefore, this paper mainly used the low-frequency triangular wave as the excitation magnetic field, and validated the theoretical model of magnetic nano-temperature measurement through experiments. During the experiment, we found that the two parameters of the average effective magnetic moment and the excitation magnetic field strength can affect the accuracy of temperature measurement in the model. The effective magnetic moment is proportional to the effective particle size of the magnetic nanoparticles. Therefore, the particle size and the excitation magnetic field are optimized to determine the particle size and the excitation magnetic field, so that the magnetic nanometer temperature measurement method can obtain higher temperature measurement accuracy by using the low frequency triangular wave magnetic field excitation. High temperature measurement accuracy enables it to be used in applications where temperature measurement is critical.

II. MAGNETIC NANOMETER TEMPERATURE MEASUREMENT THEORETICAL MODEL

According to physicist P. Langevin, the static magnetization response of superparamagnetic magnetic nanoparticles follows the Langevin's equation and it is expressed as:

$$M = nmL(\xi) = nm\left(\coth \xi - \frac{1}{\xi}\right) \quad (1)$$

Where $\xi = mH / (kT)$, n is the concentration of magnetic nanoparticles, m is the average effective magnetic moment, H is the excitation magnetic field, k is the Boltzmann constant, and T is the absolute temperature. According to the Langevin's equation model, a binary matrix equation for the temperature and concentration information of magnetic nanoparticles are constructed by using discrete excitation magnetic fields $H = [H_1, H_2, \dots, H_n]$ and corresponding magnetization $M = [M_1, M_2, \dots, M_n]$. The matrix equation is as follows:

$$\begin{cases} M_1 = x(\coth(yH_1) - 1/yH_1) \\ M_2 = x(\coth(yH_2) - 1/yH_2) \\ \vdots \\ M_i = x(\coth(yH_i) - 1/yH_i) \\ \vdots \\ M_n = x(\coth(yH_n) - 1/yH_n) \end{cases} \quad (2)$$

Where $x = nm$, $y = m/(kT)$. To solve the temperature according to equation (2), it is necessary to acquire the discrete excitation magnetic field points and the discrete magnetization points of the corresponding samples in real time. Therefore, using the time-varying magnetization response of the magnetic nanoparticles under the low-frequency triangular wave excitation magnetic field, the discrete values of the excitation magnetic field and the magnetization are obtained from the real-time, and the temperature measurement model is used for temperature inversion.

III. INFLUENCE AND OPTIMIZATION OF MODEL PARAMETERS ON MEASUREMENT ACCURACY

A. The Problems discovered by the experiment

We verified the measurement principle by experiment. Experiment used the magnetic fluid sample SHP-10 with an average particle size of 10 nm to measure the time-varying magnetization response curve of the magnetic fluid sample at different temperatures, and the magnetization curve after the period average treatment under the magnetic measurement system excited by the triangular wave magnetic field. As shown in Fig. 1.

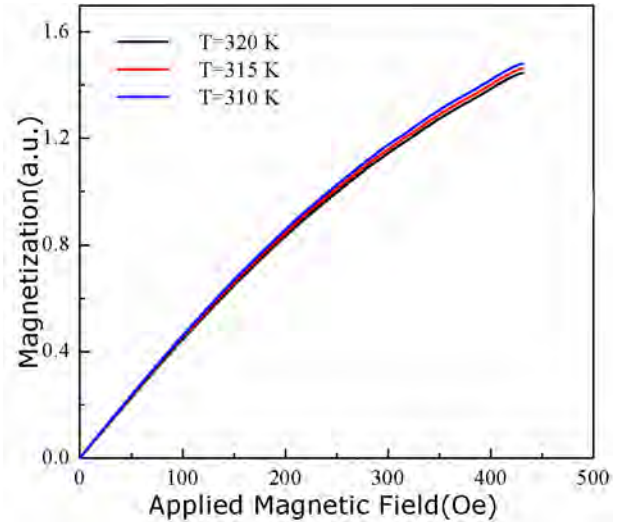


Fig. 1. Magnetization curve of magnetic fluid sample at different temperatures

Fig. 1 shows normalized magnetization curve after periodic average processing of the superparamagnetic magnetic fluid SHP-10 by a magnetic wave measurement system excited by a triangular wave at a temperature of 320 K, 315 K and 310 K respectively. The temperature is inverted based on the temperature measurement model in the temperature range of

320 K to 310 K. Select the excitation field discrete point to be 10 Oe to 390 Oe, the discrete step size is 20 Oe, and calculate the temperature error in the inversion as shown in Fig. 2. As can be seen from the figure, the maximum error is 0.75 K and the standard deviation of the temperature error is 0.29 K. On the one hand, this experiment proves the feasibility of the temperature measurement method under the triangular wave excitation magnetic field, but on the other hand, the error is slightly too large for the application field of magnetic hyperthermia. Therefore, it is necessary to study and optimize the relevant parameters in the temperature measurement model to improve the accuracy of temperature measurement.

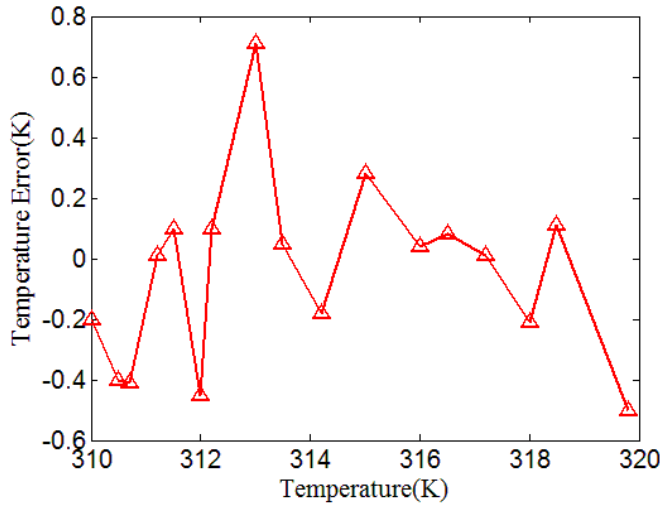


Fig. 2. Temperature error by using sample SHP-10.

In solving the temperature measurement model (2), the magnitude of the parameter $\xi = mH/(kT)$ in the Langevin's equation directly affects the Taylor expansion form of the model and the nonlinearity of the magnetization curve, which in turn affects the accuracy of the temperature measurement. The parameter ξ includes the average effective magnetic moment m and the excitation magnetic field strength H , so both parameters have an influence on the temperature measurement accuracy.

B. Optimization of particle size parameters

In order to study the key factors affecting the measurement of magnetic nanometer temperature, firstly, the influence of the effective magnetic moment of magnetic nanoparticles is studied on the accuracy of temperature measurement. We conducted a simulation experiment on this. In the simulation experiment, in order to ensure the superparamagnetism of the magnetic nanoparticles in the simulation, the average effective magnetic moment is set to $m_1=2 \times 10^{-19}$ emu, $m_2=4 \times 10^{-19}$ emu, $m_3=8 \times 10^{-19}$ emu, $m_4=16 \times 10^{-19}$ emu and $m_5=32 \times 10^{-19}$ emu. Set the same excitation magnetic field 0 Oe to 75 Oe under these five average effective magnetic moments, with a step interval of 7.5 Oe, abbreviated as 0: 7.5: 75 Oe, the same below. According to the temperature measurement model, the temperature is simulated and inverted under different mean effective magnetic moments. The standard deviation of the temperature measurement error is shown in Fig. 3.

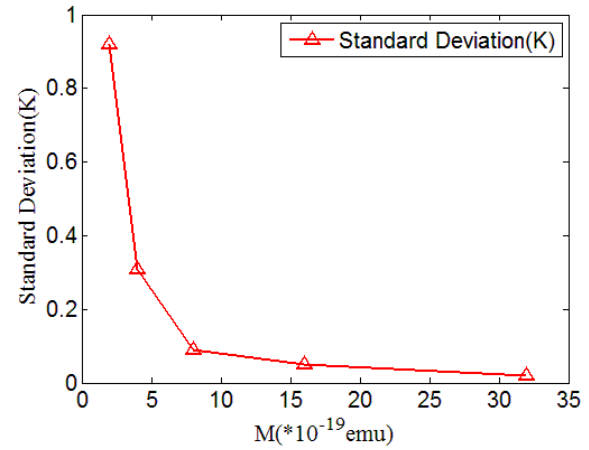


Fig. 3 shows the standard deviation of the corresponding temperature error. The simulation experiment set signal-to-noise ratio as 80 dB.

It can be seen from Fig. 3 that as the average effective magnetic moment of the magnetic nanoparticles gradually decreases, the standard deviation of the measured temperature error increases, and the measurement accuracy of the temperature gradually decreases. When the average effective magnetic moment is 2×10^{-19} emu, the standard deviation of the temperature error is reduced from 0.9 K to 0.03 K, and the accuracy is increased by about 30 times.

In order to verify the influence of the average effective magnetic moment on the temperature measurement through experiments, firstly, different average effective magnetic moments are selected according to the effective magnetic moment formula (3).

$$m = M_s V = (\sigma \rho) \cdot V \quad (3)$$

For survivability

Where M_s is the saturation magnetization, V is the effective volume of the magnetic nanoparticles, σ is the specific saturation magnetization, and ρ is the density of the material. We found that the effective magnetic moment is proportional to the effective particle size of the magnetic nanoparticles, so that the magnetic nanoparticles with different particle sizes can be selected to verify the influence of different average effective magnetic moments on the temperature measurement accuracy. In view of this, four different magnetic particle samples of different particle sizes were purchased during the experiment, which were purchased from Ocean NanoTech's water-based magnetic fluid samples. The main components were $\gamma\text{-Fe}_2\text{O}_3$ and Fe_3O_4 . Table I shows the saturation magnetization information of the purchased samples.

TABLE I. THE SATURATION MAGNETIZATION OF THE MAGNETIC FLUID SAMPLE USED IN THE EXPERIMENT

Water-based magnetic fluid model	Particle size D_c (nm)	Specific saturation magnetization σ (emu/g)
SHP-10	10	49.8
SHP-15	15	55.1
SHP-20	20	62.5
SHP-25	25	67.2

The above four samples were heated to 330 K in a water bath and naturally cooled to 300 K. We took the temperature range of 320K to 310K. The excitation magnetic field was $H = 0 : 10 : 150\text{Oe}$, and the signal-to-noise ratio of the measurement system was about 75 dB. The temperature measurement model(2) was used to perform temperature inversion and we compare their temperature measurement accuracy. The measurement results are shown in Table II.

TABLE II. THE SATURATION MAGNETIZATION OF THE MAGNETIC FLUID SAMPLE USED IN THE EXPERIMENT

Water-based magnetic fluid	Maximum measurement error (K)	Standard deviation of temperature error (K)
SHP-10	2.71	1.21
SHP-15	0.47	0.22
SHP-20	0.28	0.14
SHP-25	0.21	0.10

It can be seen from Table II that as the effective particle size of the magnetic nanoparticles increases, the average effective magnetic moment of the sample increases, and the temperature measurement accuracy increases from 1.21K to 0.1K.

C. Optimization of excitation magnetic field parameters

In the parameter $\xi = mH/(kT)$, in order to study the influence of different excitation magnetic field H on temperature measurement accuracy, the five average effective magnetic moments in the simulation of the previous section. In this section, the temperature measurement accuracy can be observed by scaling up or reducing the exciting magnetic field so as to remain unchanged. In order to ensure the consistency of the discrete points of the excitation magnetic field, the different excitation magnetic field ranges are set to $H1 = 0:120:1200$ Oe, $H2 = 0:60:600$ Oe, $H3 = 0:30:300$ Oe, $H4 = 0:15:150$ Oe and $H5 = 0:7.5:75$ Oe in the simulation experiment. That is to keep mH unchanged, other simulation conditions remain unchanged as in the previous section. the temperature error results are shown in Fig. 4.

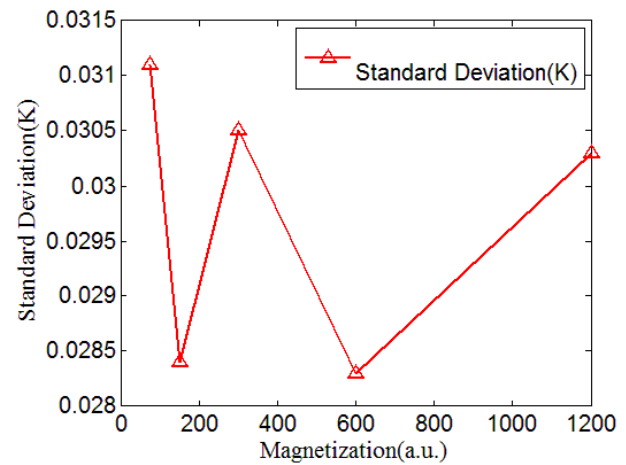


Fig. 4. Keep unchanged, comparison of the standard deviation of temperature error at five different average effective magnetic moments after the same scale is amplified or reduced by the same scale

It can be seen from Fig. 4 that the standard deviation of the temperature error is on the same order of magnitude (about 0.03 K) with little change under these five average effective magnetic moments. Comparing Table 2, we find that when the average effective magnetic moment of the particle is small, the accuracy of the temperature measurement can be improved by increasing the excitation. Conversely, for relatively large effective magnetic moment particles, the excitation magnetic field can be correspondingly reduced to achieve the purpose of improving accuracy.

In order to highlight the simulation results, the experiment selected a sample with a smaller particle size. It is SHP-10 magnetic fluid sample. Its particle size is 10 nm. According to the above simulation experiment, in order to maintain the same discrete number of points, we set up 5 different discrete excitation magnetic fields, which are $H1 = 0:10:95$ Oe, $H2 = 0:20:185$ Oe, $H3 = 0:30:275$ Oe, $H4 = 0:40:365$ Oe and $H5 = 0:45:410$ Oe. After the same temperature inversion process, the obtained temperature error measurement results are shown in Table III.

TABLE III. COMPARISON OF TEMPERATURE MEASUREMENT ACCURACY UNDER DIFFERENT DISCRETE EXCITATION MAGNETIC FIELDS

Discrete excitation magnetic field (Oe)	Maximum measurement error (K)	Standard deviation of temperature error (K)
H1	4.58	1.92
H2	1.17	0.53
H3	0.61	0.33
H4	0.48	0.29
H5	0.48	0.28

It can be seen from Table III that we find that as the range of the excitation magnetic field increases, the standard deviation of the corresponding temperature error decreases from 1.92K to 0.28K. Therefore, it can be found through experiments that the accuracy of magnetic nanometer temperature measurement increases with the increase of the

applied excitation magnetic field for magnetic nanoparticles with smaller particle diameters.

IV. OVERALL DISCUSSION OF PARAMETER ξ

Regardless of the average effective magnetic moment m or the excitation magnetic field H , it can be attributed to the influence of the parameter $\xi = mH/(kT)$, m and H affect the variation of ξ , thus they affect the accuracy of the nonlinear matrix equations. They ultimately affect the measurement accuracy of the temperature. Therefore, if the optimal range of ξ is found to maximize the temperature measurement accuracy, the most suitable excitation magnetic field or sample can be found to optimize the temperature measurement accuracy regardless of the sample selection or excitation field selection.

In the parameter ξ , mH is regarded as the whole to discuss the temperature measurement accuracy, and we found the optimal range of mH . In the simulation experiment, the starting point of mH is set to zero, and the solution is solved according to the temperature measurement model. The temperature range is set from 310 K to 320 K, and we obtained the temperature measurement accuracy by the simulation. The temperature measurement accuracy is shown in Fig. 6. In the figure, the abscissa indicates the maximum value of the range of mH values. In the whole simulation, mH is not discretized to eliminate the error which is caused by discretization.

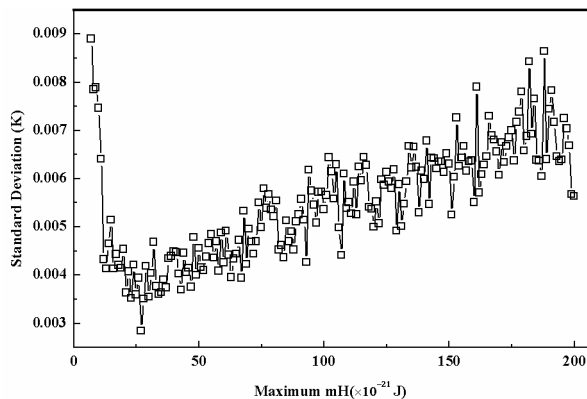


Fig. 6. Temperature measurement accuracy at different mH with a signal-to-noise ratio of 80 dB.

It can be seen from Fig. 6 that as the range of mH values increases, the measurement accuracy increases first and then decreases slightly. According to the simulation results, when the value range of mH is $(0: 21 \times 10^{-21})$ J to $(0: 28 \times 10^{-21})$ J, it is optimal, and the temperature measurement accuracy is the highest. In other words, after selecting a certain sample of magnetic nanoparticles, the optimal excitation magnetic field size can be found to maximize the temperature measurement accuracy.

V. CONCLUSION

The average effective magnetic moment and excitation magnetic field are the key factors. They affect the accuracy of magnetic nanometer temperature measurement. Under the same excitation magnetic field, as the average effective magnetic moment of the magnetic nanoparticles decreases, the ξ decreases, then it results in a gradual decrease in the accuracy of the temperature measurement. At this time, the excitation magnetic field increases in the same proportion, and the ξ is kept constant, so that the accuracy is kept in the same order of magnitude under the different average effective magnetic moment. This means that the accuracy will gradually increase as the magnitude of the excitation magnetic field increases with a small average effective magnetic moment. Therefore, for the superparamagnetic magnetic nanoparticles of smaller particle size, increasing the excitation magnetic field can improve the accuracy of the temperature measurement. After selecting a magnetic nanoparticle sample, the optimal excitation magnetic field size can be found to maximize the temperature measurement accuracy.

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