A possible temperature measurement model for fuel cell

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Abstract. In this paper, an improved temperature measuring model for fuel cell temperature measurement is proposed based on the existed nanothermometer model, which is regarded as traditional temperature measuring model. With more realistic cases taken into consideration, the results of the improved model are more practical and accurate compared with the traditional one. Limited by the existed experimental conditions, this paper emphases on simulating the different conditions of the temperature distribution inside SOFC. As a result, the experiments are carried out with similar temperature distribution but under relatively lower temperatures, which can come to similar conclusions as by simulation.

1. Introduction

Solid Oxide Fuel Cell (SOFC) is a most promising renewable energy technology based on the present energy system. When the cell stack works normally, the non-uniform temperature distribution will shorten the lifetime of the cell [1-3], thus, it is urgent to precisely acquire its temperature distribution within Solid Oxide Fuel Cell (SOFC) to make corresponding adjustment for better working environment.

According to the gradient magnetic field space coding technology used in nanoparticle concentration imaging [4-7], there will be a series of zero magnetic field points to realize the spatial location coding in the one-dimensional imaging region. Magnetic nanoparticles are at magnetization saturation state outside these zero magnetic field points, only those nanoparticles at zero magnetic field points can be induced with time-variant magnetization signals under the AC excitation magnetic field, and then the signals are probed by receiving coils. The magnetization signals acquired can provide us with temperature information.

It is better to ensure the reliability of SOFC when the temperature gradient is 10°C /cm [10], that is to say, the temperature information within 1cm needs to be acquired to judge whether the temperature gradient exceeds the safe limit, which can provide evidence for performance management of SOFC. Thus, it requires the resolution of temperature distribution is at least 1cm when conducting temperature imaging. As a result, in one-dimension temperature measurement, the distance between two points is set as 1cm.

The traditional model considers that surrounding particles have no effect on the measured point. However, the surrounding particles still have magnetization response under the AC magnetic field, which can influence the measured point. Regardding the mixed magnetization harmonic signal as the target signal to be measured,the traditional model is improved.

2. Temperature measurement model

2.1. Traditional model

To simplify the temperature measurement model, the three-point condition is considered. Assuming the location of the three points to be measured inside the fuel cell is shown as in figure 1, the space distance among these points is 1cm, and the arrow indicates the positive direction of mixed magnetic field. When acquiring the temperature at point O, the traditional model considers the gradient magnetic field imposed is strong enough to saturate the nanoparticles at the point A and B, so ignoring their influence on the measured point O.

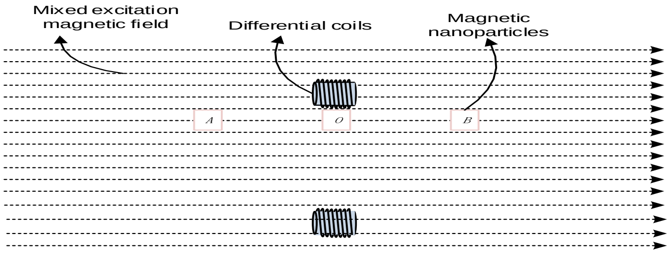

Figure 1. Magnetic nanoparticles arrangement inside SOFC

Extracting the first and the third harmonic amplitude of the magnetization response signal to invert to the value of the corresponding temperature. Retrieving temperature is mainly based on Langevin theory, according to which, for the ideal superparamagnetic nanoparticles with a single size, whose magnetization and temperature have a functional relationship described as follows [8,9]:

$$\mathrm{M} = \mathrm{N}m_s L(\eta) = \mathrm{N}m_s\left(\coth(\eta) - \frac{1}{\eta}\right) = \mathrm{N}m_s(\coth\left(\frac{m_s H}{kT}\right) - \frac{kT}{m_s H}) \quad (2.1)$$

$\mathrm{L}(\eta) = \coth(\eta) - \frac{1}{\eta}$ is Langevin function, of which $\eta = \frac{m_s H}{kT}$, N stands for particle concentration, m_s is saturation magnetization of a single magnetic nanoparticle, H is excitation magnetic field, k is Boltzmann constant and T is thermodynamic temperature.

The mathematical model of harmonic amplitude and temperature can be established by Fourier expansion for Langevin equation. Assuming sinusoidal magnetic field is expressed as $\mathrm{H} = H_0\sin(\omega t)$, the first and the third harmonic amplitude C_1 , C_3 of the magnetization M are expressed as follows:

$$\begin{cases} C_1 = \frac{NM_s^2 H_0}{3kT} - \frac{NM_s^4 H_0^3}{60k^3T^3} + \frac{NM_s^6 H_0^5}{756k^5T^5} - \frac{NM_s^8 H_0^7}{8640k^7T^7} + \cdots \\ C_3 = \frac{NM_s^4 H_0^3}{180k^3T^3} - \frac{NM_s^6 H_0^5}{1512k^5T^5} + \frac{NM_s^8 H_0^7}{1440k^7T^7} + \cdots \end{cases} \quad (2.2)$$

After obtaining the amplitude C_1 , C_3 and the saturation magnetization M_s of the magnetic nanoparticle, the temperature of the measured magnetic nanoparticles can be obtained using appropriate inversion algorithm.

2.2. Improved model.

In fact, the provided gradient field cannot eliminate the impact of surrounding nanoparticles completely. When point O is imposed by sinusoidal magnetic field, the magnetic response of nanoparticles at the three points can also produce periodic changes to affect measurement accuracy.

In order to improve the precision, an improved measurement model is proposed. The first harmonic amplitude of magnetic nanoparticles at point A, O, B have certain functional relationship with temperature, so the measurement of a mixed harmonic amplitude at point O can be expressed as:

$$C_1 = C_1^O + C_1^A + C_1^B = f_O(T_O) + f_A(T_A) + f_B(T_B) \quad (2.3)$$

When $\mathrm{T} = \mathrm{T}_o = T_A = T_B$, (2.3) can be simplified as: $C_1 = f_1(T)$. If regarding the mixed first harmonic signal C_1 as the harmonic signal at point O, the corresponding temperature value will be obtained by the fitting relationship. However, the temperatures of three points cannot completely equal, which will influence the measurement accuracy of this model.

3. Simulation analysis

3.1. Simulation analysis of traditional model

The normal working temperature of SOFC ranges between 650℃ and 850℃, in order to analyze how large gradient magnetic field needed to meet the measurement accuracy requirements in traditional model, the Cobalt with average size of 20nm is selected as the temperature sensitive element for its high Curie temperature, the space interval among A, O and B is set as 1cm, and carrying out simulations using MATLAB.

To observe the performance of SOFC when working normally, the simulation temperature is set as 650℃, 750 ℃, 850℃ and 950 ℃, it usually considers uniform temperature distribution in this model, so the temperatures of three points are the same, the excitation AC magnetic field applied is 15 ~ 45 Oe, the step is 3 Oe and the AC magnetic field frequency is 375Hz; the gradient magnetic field needed to achieve the resolution is defined as the basic gradient field G_0, during the simulation, the gradient magnetic field set as $1G_0$, $3G_0$, $5G_0$, $8G_0$. The temperature errors are shown in figure 2.

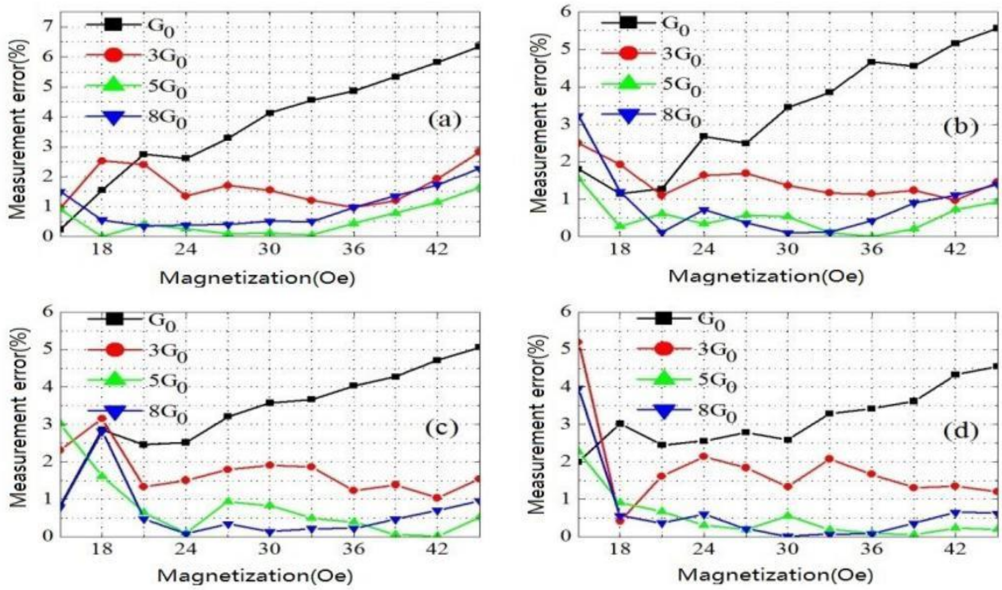

Figure 2. Temperature errors in traditional model. a,b,c,d is respectively the simulation result at 650℃, 750℃,850℃,950℃

In figure 2, the temperature error under $5G_0$ is obviously smaller than that under G_0, and the temperature error under $8G_0$ is close to that under $5G_0$, the measurement accuracy did not significantly improve, so further increasing the gradient magnetic field on temperature measurement precision is of little help. There are similar results under the four different temperatures.

Then we can conclude: to eliminate the interference of magnetic nanoparticles around the measured point to ensure the temperature measurement error is reduced to less than 1%, the gradient magnetic field needed must be more than 5 times of the basic gradient field.

3.2. Simulation analysis of the improved model

In improved model, the impact of surrounding nanoparticles on measured point is under consideration. The temperature difference within 1cm is better not bigger than 10℃, and the maximum temperature difference is 50℃, in actual work, temperature fluctuation cannot be avoided, the temperature gradient can easily reach 20℃/cm. Thus, taking the normal working case and the limit case into consideration, the simulated temperature difference within 1cm is set as 20 ℃ and 50 ℃.

Due to the low and high temperature state of SOFC when it works normally respectively are 650℃ and 850℃, which have typical representativeness to set them as simulation temperatures. It usually considers non-uniform temperature distribution in this model.

According to different changing ways of temperature, there are two cases of temperature gradient in non-uniform temperature distribution: case1. temperature of central point is higher than surrounding points; case2. temperature of one point is higher than the temperature of central point, and the other's is lower than it. Considering two temperature gradients, when setting the temperature of the central point O as 650℃, A-O-B temperature distribution still has four cases: 630℃-650℃-630℃，630℃-650℃-670℃，600℃-650℃-600℃，600℃-650℃-700℃. Similarly, there are also four conditions at 850℃: 830℃-850℃-830℃，830℃-850℃-870℃，800℃-850℃-800℃，800℃-850℃-900℃. The temperature errors are shown in figure 3 and figure 4.

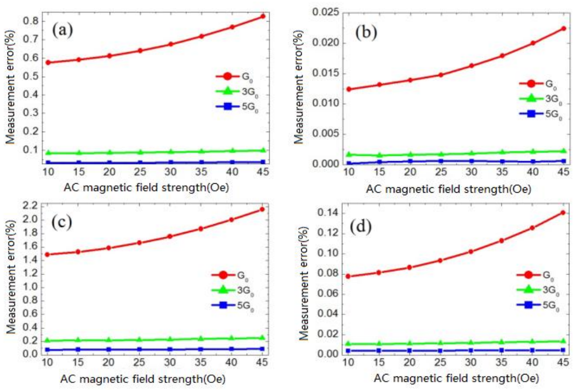

Figure 3. Measurement errors at 650℃. a. 630℃-650℃-630℃, b. 630℃-650℃-670℃, c. 600℃-650℃-600℃,d. 600℃-650℃-700℃.

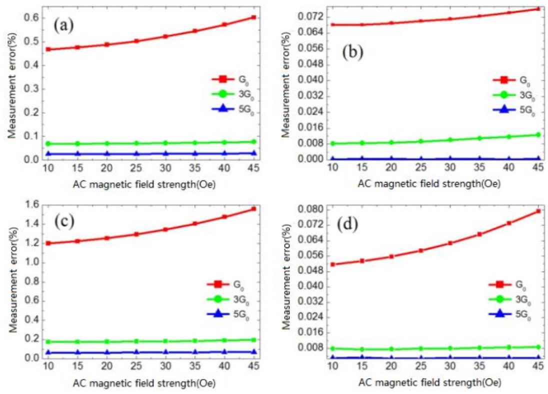

Figure 4. Measurement errors at 850℃.a. 830℃-850℃-830℃, b. 830℃-850℃-870℃,c. 800℃-850℃-800℃, d. 800℃-850℃-900℃.

It can be seen from figure 3 and figure 4 that only imposing the basic gradient field G_0 on the magnetic nanoparticles, the measurement error is large for adjacent particles being not completely saturated. While the gradient field set as $3G_0$, the measurement error is significantly reduced. Although the measurement error under $5G_0$ is also reduced, the accuracy improvement is not obvious. And respectively analyzing the four cases in 650℃ and 850℃, there is another conclusion: when the temperature gradient reaches to 50℃/cm, the error is larger than that is 20℃/cm.

When the temperature fluctuation is within 50℃, setting the gradient field as $3G_0$ ensures the measurement error less than 0.2%.Limited by series of realistic conditions, strong gradient field is hard to produce, thus, compared with traditional model, the improved model leads to smaller measurement error with relatively lower gradient field, which is favour of realization in practice.

4. Experimental verification

Fe_3O_4 has similar magnetic properties as Co, but much larger magnetization response, it is used as temperature sensitive element in experiments to observe the experimental results obviously. It is difficult to complete the experiments under normal working temperature of SOFC in the lab, and it cannot keep the temperature constant, so similar cooling experiments can be carried out under relatively lower temperatures.

4.1. Uniform temperature distribution

In this condition, we assume the temperature of point A, O, B are the same. Applied by gradient field, the same amount of nanoparticles are placed at these points, after bath heating and then natural cooling(365K-room temperature), using two models to get the corresponding temperatures, compared with the measuring values obtained by optical fiber thermometer, then we can get the corresponding temperature errors.

In figure 5, in the upper scheme, the blue line indicates the temperature measured by thermometer and the red line indicates the temperature calculated by traditional model, the bottom scheme shows corresponding temperature errors. Similarly, the temperature information in figure 6 is obtained by improved model.

We can see that the maxim temperature error can reach up to 7.17K by traditional model and it is only 0.56K by improved model. Thus, under this condition, the measurement result obtained by improved model is more accurate.

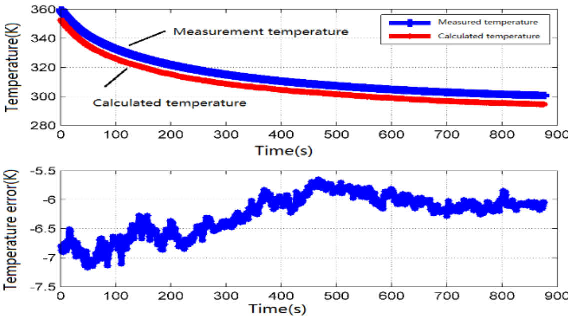

Figure 5. Temperature measurement by traditional model

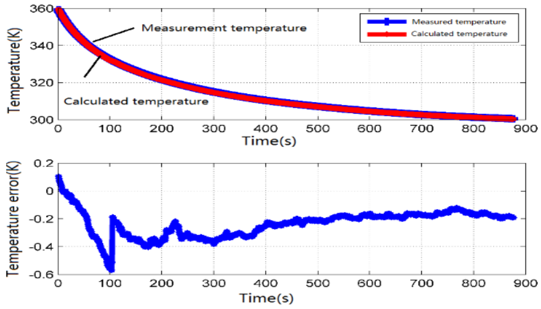

Figure 6. Temperature measurement by improved model

4.2. Non- uniform temperature distribution

In this condition, we assume the temperature of point A, O, B are different. As mentioned above, there are two cases of temperature gradient in non-uniform temperature distribution, thus, two groups of experiments were designed. In experiment 1, point O is naturally cooled (365K -room temperature), point A and B are at room temperature; in experiment 2, point A is at room temperature, point O and B are naturally cooled (365K -room temperature, 415K -room temperature).

These two experiments are carried out and then respectively analysed by traditional model and improved model. Test results are shown as followed.

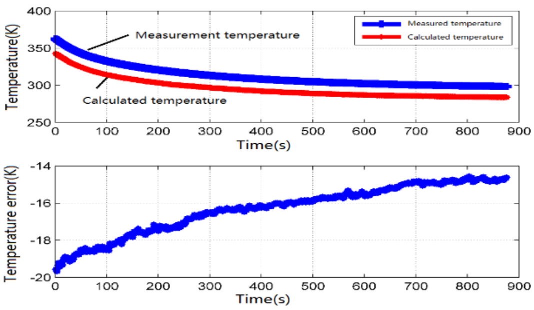

Figure 7. Temperature measurement by traditional model(experiment 1)

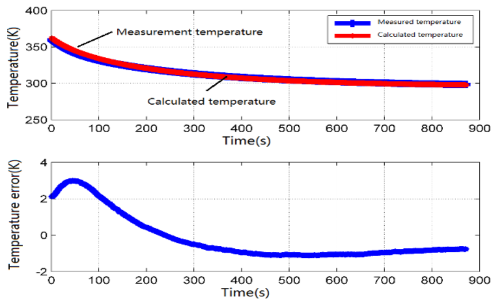

Figure 8. Temperature measurement by improved model(experiment 1)

From figure 7 and figure 8, we can see that in the experiment 1, traditional model has the maximum temperature error of 19.68K and improved model has the maximum temperature error of 3.00K.

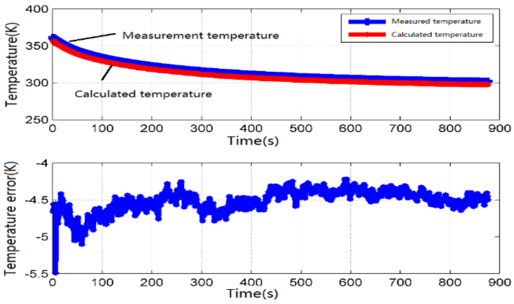

Figure 9. Temperature measurement by traditional model(experiment 2)

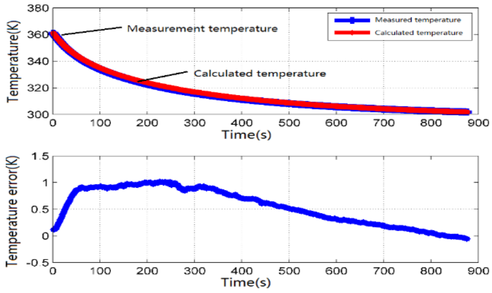

Figure 10. Temperature measurement by improved model(experiment 2)

From figure9 and figure10, we can see that in the experiment 2, traditional model has the maximum temperature error of 5.48K and improved model has the maximum temperature error of 1.02K.

Thus, we can conclude : the whole errors in experiment 2 is smaller than that in experiment 1, which indicates that linearly temperature variation is good for temperature measurement, and in the case of uniform or non-uniform temperature distribution , the improved model can exactly improve the measurement accuracy.

5. Conclusions

Using the magnetic nanoparticles, we propose an improved temperature measurement model on the basis of the existed nanothermometer model to optimize the measuring accuracy when obtaining the internal temperature distribution of SOFC at normal operating temperature (650℃~ 850℃).We analysed these two models by simulation and make corresponding experiments.

By simulation, we conclude that the traditional temperature measurement model needs more than $5G_0$ to ensure temperature measurement error reduce to below 1%, but in improved model, when the gradient magnetic field is $3G_0$, the measurement error can be controlled below 0.2%. This greatly reduces the design requirements of the gradient magnetic field coil and the power supply, which contributes to practical application.

In the experiments, using Fe_3O_4 nanoparticles as a temperature sensitive element, and analogy different conditions of temperature distribution inside SOFC, then obtaining the temperature measurement errors by the two measuring models, compared to the traditional model, the improved one can indeed improve the temperature measurement accuracy.

In conclusion, the improved temperature model is more practical and has higher measurement accuracy, which is appropriately regarded as a possible temperature measurement method in fuel cell.

References

[1] A.A. Kulikovsky, *A simple equation for temperature gradient in a planar SOFC stack*, International Journal of Hydrogen Energy, 35 (2010) 308-312.

[2] W.B. Guan, H.J. Zhai, L. Jin, C. Xu, W.G. Wang, *Temperature Measurement and Distribution Inside Planar SOFC Stacks, Fuel Cells*, 12 (2012) 24–31.

[3] C.K. Lin, L.H. Huang, L.K. Chiang, Y.P. Chyou, *Thermal stress analysis of planar solid oxide fuel cell stacks: Effects of sealing design*, Journal of Power Sources, 192 (2009) 515-524.

[4] M. Gruettner, M. Graeser, S. Biederer, T.F. Sattel, *1D-image reconstruction for magnetic particle imaging using a hybrid system function*, 3338 (2011) 2545-2548.
2013.

[5] T. Knopp, S. Biederer, T. Sattel, J. Weizenecker, B. Gleich, J. Borgert, T.M. Buzug, *Trajectory analysis for magnetic particle imaging*, Physics in Medicine & Biology, 54 (2009) 385-397.

[6] P.W. Goodwill, S.M. Conolly, T*he X-space formulation of the magnetic particle imaging process: 1-D signal, resolution, bandwidth, SNR, SAR, and magnetostimulation*, IEEE Transactions on

Medical Imaging, 29 (2010) 1851-1859.
[7] T. Knopp, T.F. Sattel, S. Biederer, J. Rahmer, J. Weizenecker, B. Gleich, J. Borgert, T.M. Buzug, *Model-Based Reconstruction for Magnetic Particle Imaging*, IEEE Transactions on Medical Imaging, 29 (2010) 12-18.
[8] F. Ludwig, D. Eberbeck, N. Löwa, U. Steinhoff, T. Wawrzik, M. Schilling, L. Trahms, *Characterization of magnetic nanoparticle systems with respect to their magnetic particle imaging performance*, Biomedizinische Technik/biomedical Engineering, 58 (2013) 535.
[9] A. Lak, F. Ludwig, J.M. Scholtyssek, J. Dieckhoff, *Size Distribution and Magnetization Optimization of Single-Core Iron Oxide Nanoparticles by Exploiting Design of Experiment Methodology*, IEEE Transactions on Magnetics, 49 (2013) 201-207.
[10] N. Akhtar, S.P. Decent, K. Kendall, *Cell temperature measurements in micro-tubular, single-chamber, solid oxide fuel cells (MT–SC–SOFCs)*, Journal of Power Sources, 195 (2010) 7818–7824.