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MPI coil temperature stabilization method based on phase change heat storage technology

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Abstract

In magnetic particle imaging systems, it is necessary to pass a high current through the coil or to run it for a long time to perform a specific function. These generate a large amount of Joule heat in the coil, which introduces additional thermal noise and affects system stability. In this work, we propose a method to control the coil temperature of magnetic particle imaging device based on phase change thermal storage technology by exploiting the latent heat properties of phase change materials. The simulation experiments show that the method makes the coil temperature remain almost constant and suppresses the problem of temperature variation of the energized wire. Compared with active temperature control methods such as liquid helium cooling , oil cooling and water cooling, this method has the advantages of low cost, small size, and good portability.

I. Introduction

In magnetic particle imaging (MPI) systems, it is generally necessary to pass a high current to the excitation coil for functions such as scanning field, selection field, and focus field. The strength of the magnetic field depends on the amount of current passing through it. For some modes that require continuous operation, the coil must also be energized for a long time. For example, several consecutive measurements are required for acquiring system matrix. Therefore, a large amount of Joule heat will be generated on the coil, and the heat generated on the coil will gradually accumulate as time grows, resulting in the nonstationary background signal, reducing the signal to noise ratio. The heat also changes the impedance characteristics of the coil itself, increasing the noise of the generated image and seriously affecting the system's stability [1]. This part of thermal noise often cannot be completely filtered out by signal processing methods such as software filtering. In summary, the addition of temperature control equipment to MPI is necessary.

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Currently, in MRI, liquid helium cooling is commonly used to keep the superconducting magnet at a very low temperature so that the coil is in operation. However, liquid helium is expendable and requires constant addition of liquid nitrogen for continuous cooling, resulting in large and expensive cooling equipment [2]. In MPI, liquid refrigeration and other active temperature control methods are used. Hollow copper wires are generally used as coils to generate magnetic fields. The refrigerant flows inside the hollow coil, so as to take the heat away and realize the coil temperature control. Which is widely used because the coolant in full contact with the copper tube gives competitive advantages of high thermal conductivity and heat transfer capacity [3]. However, this scheme can only cool down the copper tube and cannot do anything for the Litz line under high frequency excitation. Moreover, all these methods require additional liquid-cooled circulating units with large sizes and additional electrical energy, which increases the installation and maintenance costs. In this paper, we take advantage of the characteristics of PCM in absorbing large amounts of latent heat during phase change and apply them to the coil temperature control of MPI devices. We propose a coil temperature stabilization control method for magnetic nanoparticle imaging devices based on phase change thermal storage technology.

II. Material and methods

II.I. Phase change materials

PCM are materials that can store large amounts of heat at nearly uniform temperatures when transitioning from one phase state to another. For example, a phase change from a solid to a liquid state usually stores thermal energy in both sensible and latent heat forms. The sensible heat is the thermal energy stored as the temperature rises near the melting point. While latent heat is dominant, that is the thermal energy stored during the phase change. On the contrary, when the temperature decreases, the thermal energy is continuously released. Even after hundreds of thousands of phase change cycles, the PCM still retain the latent thermal energy, keeping the temperature of the object's surface almost constant [4]. The temperature change characteristic curve of a phase change material transformed from a solid to a liquid state is shown in Figure 1.

PCM have been widely used in energy saving in buildings, waste heat recovery, solar energy utilization, battery thermal management and heat dissipation in electronic devices, etc. They are promising materials. Many classical PCM, such as paraffin and polyethylene glycols, have been studied and reported [4] Among these PCM, paraffin is of great interest due to its high melting heat, broad phase change temperature, good chemical resistance, and low cost [5].

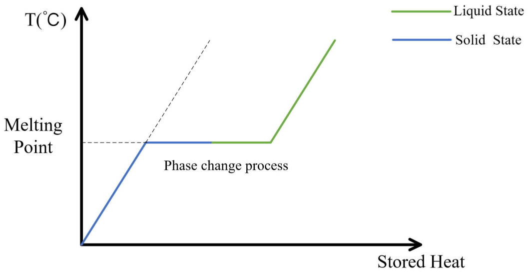

Figure 1: Temperature change characteristic curve of phase change material

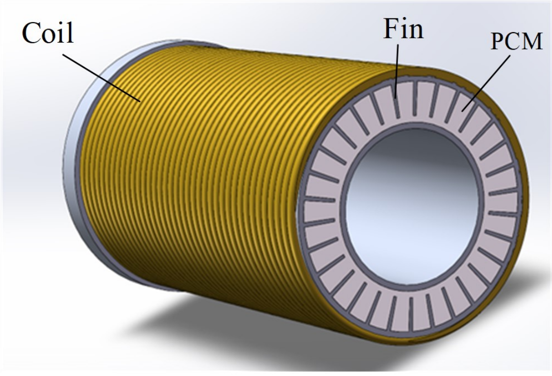

Figure 2: PCM and fin structure

Compared to conventional thermal management methods, PCM do not consume energy and do not require additional components. During the phase change process, PCM absorb or release a large amount of latent heat while maintaining an almost constant temperature. This process is accompanied by a large latent heat of phase change and small temperature and volume changes, which improves the coil temperature uniformity and keeps it within reasonable limits, which is very suitable for the temperature control of our equipment.

II.II. Models

In order to verify the effectiveness of the phase change heat storage technology in controlling the coil temperature, we established the simulation model and carried out the corresponding simulation experiments.

As shown in Figure 2, a coil model with phase change material is constructed, which consists of a coil module, a skeleton with a fin structure, and an embedded phase change material model.

The Joule heat P generated by the coil is:

$$P = I^2 \times R\,. \tag{1}$$

where I is the effective value of the current through the coil and R is the equivalent resistance value of the coil.

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Table 1: Conditions of experiment

Item	Value	Unit
Diameter of the skeleton	84	mm
Heating Power	100	W
Phase Change Material	Paraffin	/
Melting Point	26	℃
Latent Heat	260	J/g
Thermal Conductivity	0.5	W/(m·K)
Density	0.83	g/cm^3
Specific Heat Capacity	2000	J/(kg·K)

Since the thermal conductivity of the phase change material itself is relatively low, it usually needs to be used in combination with a material with high thermal conductivity. The most common design is a structure with thermal conductive fins, which can transfer the heat from the surface to the phase change material more efficiently.

The heat transfer model for PCM is generally modeled by the equivalent heat capacity method, which is [6]:

$$\nabla\cdot(\lambda\nabla T)+\dot{q}=\rho C_{eff}\frac{\partial T}{\partial t}. \tag{2}$$

where λ is the thermal conductivity, T is the temperature, $\dot{q}$ is the heat generation rate, ρ is the density, and C_{eff} is the equivalent heat capacity.

We used thermal simulation software to conduct simulation experiments on this model, and the experimental setting conditions are shown in Table 1.

III. Results and discussion

III.I. Results

The model is divided into three areas: the coil, the fin skeleton and the PCM. The original coil current heating model and coil heat dissipation model with phase change heat storage structure were designed and compared. Apply the same heat energy of 100W power to the coil, observe the temperature change at the detection point, run continuously for 200 seconds and record the data. From the experimental results, it can be seen that the solution of this paper is effective. The overall temperature is maintained in the range of 26℃ to 27℃ in the phase change region. In contrast, the temperature of the coil without the cooling system can be increased up to 48.65℃ and higher with time.

A temperature probe is placed centrally inside the coil to detect the temperature of the coil surface. The graph of temperature vs. time shows that the proposed scheme can stabilize the coil temperature near the phase transition point for a certain time without adding the cooling system, and the coil temperature is proportional to the running time. In summary, the temperature control method of MPI's coils based on phase change thermal storage technology proposed in this paper suppresses the continuous increase of coil temperature.

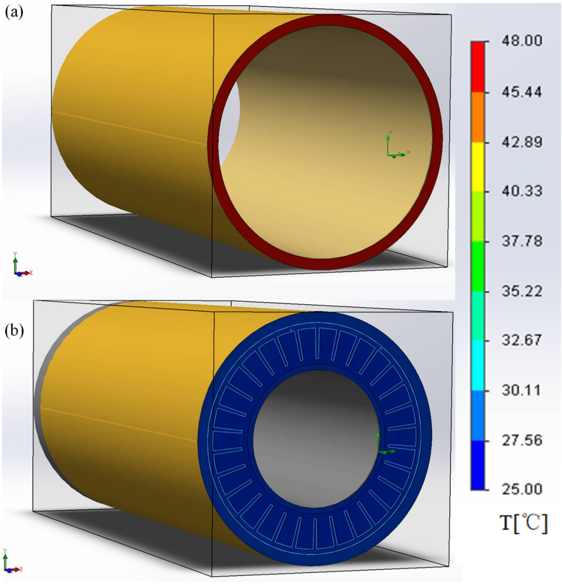

Figure 3: Comparison of temperature distribution of (a) original coil (b) PCM-coil model

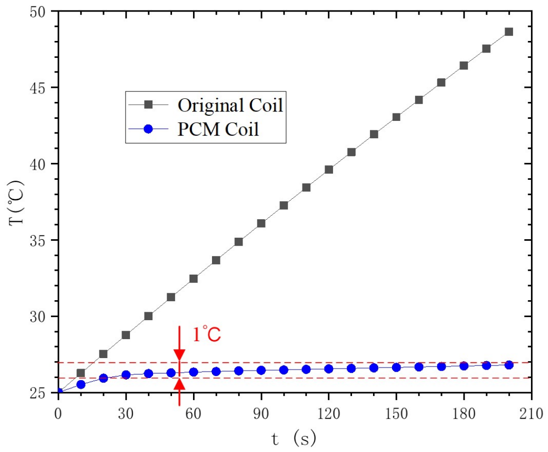

Figure 4: Temperature versus time curve

III.II. Discussion

In the last conference, Florian Thieben et al. developed a device that actively controls the temperature of the capacitor [7], which solves the phase shift problem caused by the capacitor temperature change. The method presented in this paper can also be applied to the capacitance temperature control and inductance temperature control of resonant circuits.

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IV. Conclusions

The temperature control method using phase change thermal storage technology has good application prospects. In this paper, a method of coil temperature control for MPI equipment based on phase change heat storage technology is established. When the temperature exceeds the material's phase change temperature, the device can keep the coil temperature basically at the set phase change temperature point, which solves the thermal noise caused by coil temperature drift.

The solution proposed in this paper is a passive temperature control mode, without additional energy and large equipment to achieve temperature control, with low cost, low operating cost, low failure rate, little impact on the surrounding environment, convenient and other advantages. However, because the heat absorbed depends on the characteristics and volume of phase change material, it is suitable for small aperture MPI, handheld MPI and other small MPI devices.

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Author's statement

Conflict of interest: Authors state no conflict of interest.

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