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HEATING OF A PHASE CHANGE MATERIAL VIA MAGNETIC HYSTERESIS LOSSES OF EMBEDDED FERROMAGNETIC PARTICLES

Summary

This study investigates volumetric electromagnetic heating of phase change materials (PCM) enhanced with embedded ferromagnetic particles. A systematic screening of iron-based powders and soft ferrites with defined Curie temperatures was conducted under inductive excitation and microwave irradiation. Selected materials were integrated into 1-eicosanol as the PCM to evaluate charging performance for a compact plate-warming storage unit. Particular focus is placed on intrinsic temperature limitation via Curie temperature and on heating controllability. The results demonstrate reproducible and controllable volumetric heating. Compared to graphite-based fillers, ferrite composites provide improved thermal uniformity and reduced hotspot formation. The concept enables rapid and contactless recharging of compact latent heat storage systems.

Keywords: Phase Change Materials, Magnetic Hysteresis Heating, Curie Temperature, Inductive Heating, Microwave Heating, Thermal Storage

Field of application for the findings: Compact thermal storage devices, food warming systems, catering and hospitality applications, electrically rechargeable heat storage solutions

Addressed audience: Researchers and engineers in thermal energy storage, applied electromagnetics, materials science, and heating system development

1. Introduction

Compact systems for maintaining the temperature of pre-heated food require stable thermal output combined with rapid and convenient recharging capability. Latent heat storage using phase change materials (PCM) offers high energy density and near-constant discharge temperature, making it well suited for temperature-holding applications such as plate and meal stabilization. However, conventional charging methods rely on surface-based heat transfer, which limits charging rates, reduces controllability, and may lead to thermal gradients within the storage medium.

To overcome these limitations, this study investigates an alternative approach based on volumetric heating generated by magnetic hysteresis losses of ferromagnetic particles embedded in a PCM composite and exposed to alternating electromagnetic fields. By generating heat directly inside the storage material, charging times can be reduced and temperature distribution improved compared to conventional conductive heating. This concept enables contactless and rapid recharging of compact thermal storage units designed for maintaining plate and meal temperatures over extended periods.

A key feature investigated in this work is the use of soft ferrites with defined Curie temperatures. Since magnetic hysteresis losses decrease significantly above the Curie temperature, intrinsic temperature limitation can be achieved without active control systems. This self-limiting behavior is particularly attractive for temperature-holding systems, where overheating must be avoided and operational safety is essential.

Experimental investigations evaluate heating performance under varying excitation frequencies and applied voltages using different electromagnetic field sources. In addition to inductive excitation, microwave irradiation is examined as an alternative heating method with potential advantages in system cost and integration. Temperature rise, charging time, thermal stability during discharge, and heating controllability are analyzed to assess practical feasibility.

The objective of this study is to evaluate the applicability of electromagnetically rechargeable PCM composites for compact plate temperature-holding systems and to compare inductive and microwave excitation methods in terms of performance and controllability.

2. Materials and Methods

2.1 Magnetic Particles

The following commercially available powders were investigated: iron–manganese powder, iron oxide, and magnetite. In addition, soft ferrites with defined Curie temperatures were examined. For confidentiality reasons related to industrial development, these materials are denoted as: Ferrite X60, Ferrite X100, Ferrite X120, Ferrite X130, where the number indicates the approximate Curie temperature in °C.

2.2 Screening in Silicone Composites

As a preliminary step, particles were dispersed in silicone at defined weight fractions to obtain stable model composites. This allowed reproducible comparison of heating behavior without phase change effects. Disc-shaped samples with a diameter of 150 mm and a thickness of 5 mm were produced. The composites consisted of 20 wt.% magnetic particles and 80 wt.% silicone, using a two-component addition-curing silicone system.

Samples were exposed to inductive excitation at different frequencies (e.g., 263–1364 kHz). Temperature evolution was recorded.

2.3 Microwave Testing

Microwave experiments were conducted at 2.45 GHz and 700 W to evaluate a potentially more cost-effective excitation method. Heating curves were recorded for selected particle systems.

2.4 Integration into PCM

Selected ferrite systems were incorporated into PCM composites. Temperature evolution during microwave charging was recorded to evaluate heating behavior and phase change of the PCM.

2.5 Temperature measurement

Temperature measurements were conducted using an infrared thermal imaging camera (FLIR C2, Teledyne).

3. Results and Discussion

3.1 Comparative heating under inductive excitation

The measurements were performed using silicone-based composite discs containing the magnetic particles. Ferrite X100 exhibited the highest heating performance, demonstrating the strong dependence of heating behavior on magnetic properties and Curie temperature.

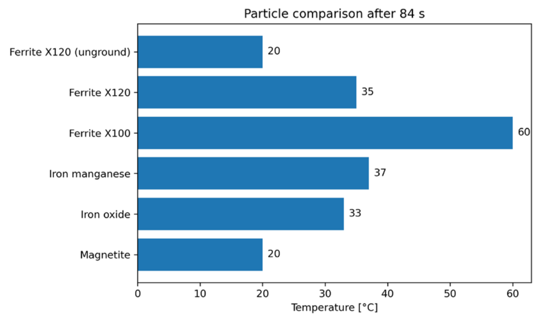

Fig. 1: Maximum temperature of different magnetic particles after 84 s under inductive excitation at 1364 kHz and 440 V

3.2 Plateau behavior under inductive excitation

Figure 2 shows the temperature evolution of the silicone-based composite containing Ferrite X100 at 263 kHz and 400 V. The temperature increased rapidly to 150 °C within approximately 100 s and subsequently reached a plateau. Such plateau behavior is advantageous for practical applications, as it reduces the risk of overheating and simplifies system control.

3.3 Induction versus microwave excitation

Microwave heating of the silicone-based composite containing Ferrite X120 (2.45 GHz, 700 W) resulted in rapid temperature increase from 23 °C to 104 °C within 40 s. As the temperature approached the Curie region, the heating rate decreased significantly; however, unlike inductive excitation, the temperature continued to increase gradually to 134 °C. This indicates strong magnetic losses below the Curie temperature and reduced, but not fully suppressed, heating above it. Induction provides higher controllability, whereas microwave excitation offers a potentially lower-cost implementation.

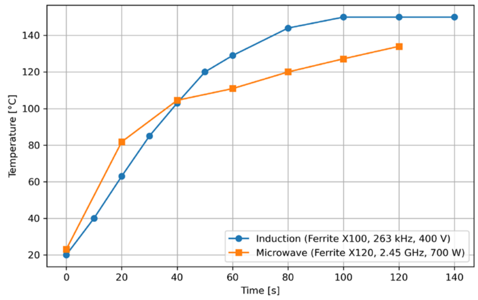

Fig. 2: Comparison of temperature evolution under inductive excitation and microwave irradiation. Inductive heating of the silicone-based composite containing Ferrite X100 shows a clear plateau behavior, whereas microwave heating of the silicone-based composite containing Ferrite X120 continues with a reduced heating rate beyond the Curie region

3.4 PCM composite performance and thermal uniformity

Ferrite X60 and Ferrite X130 were incorporated into a 1-eicosanol PCM composite at a concentration of 13 wt.%. Figure 3 illustrates the temperature evolution during microwave charging. A clear temperature plateau can be observed between approximately 50 and 60 °C, indicating the latent heat absorption during the phase change of the PCM. The composite containing Ferrite X130 exhibits a faster temperature increase, leading to a faster melting of the PCM compared to the Ferrite X60 composite.

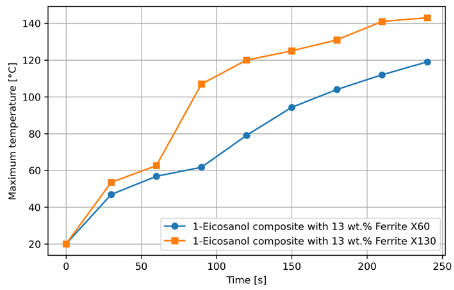

Fig. 3: Maximum temperature during microwave heating of a 1-eicosanol composite containing 13 wt.% Ferrite X60 compared with Ferrite X130

Standard deviation values remained moderate (≈11–17 °C), indicating controlled and relatively uniform heating. For comparison, graphite-filled composites exhibited extremely rapid heating but developed strong temperature gradients and hotspots under microwave exposure. In several cases, local overheating led to degradation of the PCM compound. Therefore, ferrite-based composites were selected for application-oriented development. From a system design perspective, controllability and thermal uniformity were prioritized over maximum heating rate.

4. Conclusions

This study demonstrates the feasibility of electromagnetically rechargeable PCM composites for compact temperature-holding applications for pre-heated food. The results demonstrate effective volumetric heating using embedded magnetic particles and intrinsic temperature stabilization near the Curie temperature. Clear differences between inductive and microwave excitation were observed, while ferrite-based composites showed superior thermal uniformity compared to graphite fillers, thereby enabling compact latent heat storage systems with rapid and contactless recharging.