# Numerical and experimental investigation of a phase-change material embedded in a confined space and subjected to a magnetic field

**Alissar YEHYA**[1, 2], **Philip ADEBAYO** [3], **Hassane NAJI** [4, 1]

[1] Department of Civil and Environmental Engineering, Maroun Semaan Faculty of Engineering and Architecture, American University of Beirut, Lebanon

[2] Harvard John A. Paulson School of Engineering and Applied Sciences, Cambridge, USA

[3] Department of Mechanical Engineering, Maroun Semaan Faculty of Engineering and Architecture, American University of Beirut, Lebanon

[4] Univ. Artois, IMT Nord Europe, Junia, Univ. Lille, ULR 4515, Laboratoire de Génie Civil et géo-Environnement (LGCgE), F-62400 Béthune, France

**Abstract –** In phase change materials (PCMs) applications, phase-change happens at nearly constant temperature. So, controlling the phase-change duration can be helpful to avoid thermal fluctuations. In this study, we use numerical and experimental investigation to assess the impact of using magnetic field on the phase-change process of a PCM. Our results show that the magnetic field can slow the phase-change process when Lorentz force is applied opposite to the buoyant force. This has implications on the management of latent heat storage and release to match energy demand.

**Nomenclature (11 pt, 2 columns)**

| | |
|---|---|
| $u$ | velocity, m/s |
| $p$ | pressure, Pa |
| $g$ | acceleration due to gravity, m/s$^2$ |
| $L$ | Latent heat of fusion, J/kg |
| $\boldsymbol{D}$ | Darcy source term |
| $\boldsymbol{F_l}$ | Lorentz force |
| $c_p$ | specific heat, J. kg$^{1}$. K$^{-1}$ |
| $T$ | temperature, K |
| $k$ | thermal conductivity, W.m$^{-1}$. K$^{-1}$ |
| $t$ | time, s |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | liquid fraction |
| $\rho$ | density, kg/m$^3$ |
| $\sigma$ | electrical conductivity |
| $\beta$ | coefficient of thermal expansion, 1/K |
| $\mu$ | kinematic viscosity, m$^2$/s |

*Index*

| | |
|---|---|
| $s$ | solid |
| $l$ | liquid |

## 1. Introduction

In the last decade, and due to the exponential increase in the global population, there has been a surge in energy demand, energy consumption, and $CO_2$ emissions. The building sector accounts for one-third of global energy use and 40% of overall $CO_2$ emissions [1]. The increased need for building energy consumption is mostly due to space cooling, heating, and ventilation to meet thermal comfort needs [2]. This has raised environmental concerns and has

---

[1] *Corresponding author.*
*✉ Univ. Artois, IMT Nord Europe, Junia, Univ. Lille, ULR 4515, Laboratoire de Génie Civil et géo-Environnement (LGCgE), F-62400 Béthune, France.*
*E-mail address : hassane.naji@univ-artois.fr*
*ORCID https://orcid.org/0000-0002-5994-7958*

https://doi.org/10.25855/SFT2023-116

triggered research for new and renewable energy [3]. Phase change materials are substances that have the capability to store and release a large amount of heat within a small or no temperature change [4]. Hence, energy storage with phase change materials (PCMs) can help close the energy supply and demand gap, enhance the efficiency of energy systems, and play a significant part in energy conservation [5].

Despite the advantages of the use of PCMs, one of its challenges is gradual heat storage and impulsive heat release [6]. Moreover, the cost of phase change materials is generally expensive and has been projected to be cost effective in hot climate [7]. This necessitates the need for a careful and precise energy analysis to optimally utilize PCMs [8]. In this study, we are proposing the assess the use of magnetic field to control the melting and solidification process to reduce energy consumption in buildings by optimizing the use of PCMs.

A few works have been devoted to the study of the impact of magnetic field especially on liquid metals and ferrofluid. Gui et al. [9] experimentally investigated the role of external magnetic field on heat transfer enhancement of ferrofluid under an external magnetic field. They reported an increase in the convective heat transfer rate as the solid fraction of magnetic particles increases. Doostani et al. [10] numerically studied the magnetic field effect on natural convection phase-change heat transfer of gallium in a rectangular enclosure. They reported a decrease in the rate of melting as the magnetic field strength increases. Nakhla et al. [11] introduced a novel experimental methodology to study the effect of heat transfer enhancement under the influence of electrohydrodynamic and gravitational forces on the melting of octadecane. To the best of our knowledge, no detailed experimental studies on the effect of magnetic field on phase change materials has been reported in the literature. Therefore, this paper seeks to study experimentally and numerically the effect of magnetic field on the melting and solidification of PCMs.

## **2.** Methodology

### 2.1. Experimental setup

The experimental setup is depicted in Figure 1 and is based on the work of Yehya et al [5]. Heat flux sensors, insulating materials, heat exchange plates, permanent magnets, thermoregulated bath, data acquisition systems (data logger), and control systems for the thermoregulated bath are used. The investigated phase change material (Octadecane) is placed inside an aluminum enclosure of dimensions 40mm x 40mm x 15mm and is placed between two heat exchange aluminum plates (40mm x 80mm x 10mm) controlled by the thermoregulated bath (Julabo Corio CD Model, 2.0 kW). We use neodymium magnet of dimension 40mm x 15mm x 5mm with a magnetic field strength of 240 mT. The magnet is placed at the bottom to exert a magnetic field in the vertical direction. Differential temperature heat flux sensors from FluxTeq are used to determine the heat flux and temperature in real time.

### 2.2. Numerical model

A 2D numerical model based on the continuity, momentum, and energy equations during the phase change process using the enthalpy-porosity method was implemented in OpenFOAM, an open-source Computational Fluid Dynamics toolbox based on a finite volume method. The geometry is depicted in Figure 2. Viscous dissipation as well as radiation are neglected since the material is considered to be placed in a high conductivity opaque enclosure. The flow is assumed to be laminar and incompressible and Boussinesq approximation is adopted. The model is benchmarked and validated against literature results in our recently published work [12]. It is worth noting that the experimental work was not done to verify the numerical model as the model has been benchmarked against other numerical models. The experimental results are used to support the numerical results in the conclusions since an exact comparison could not be because the electrical characteristics of the magnet to exactly estimate the Hartman number are not known.

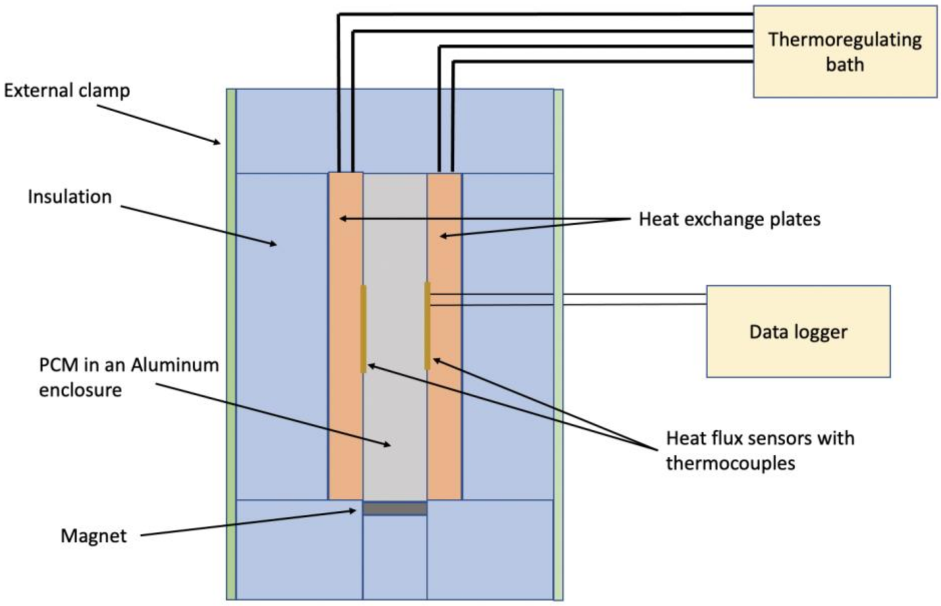

Figure 1: *Experimental setup schematic illustration. Placing the magnet at the bottom creates a magnetic field in the vertical direction*

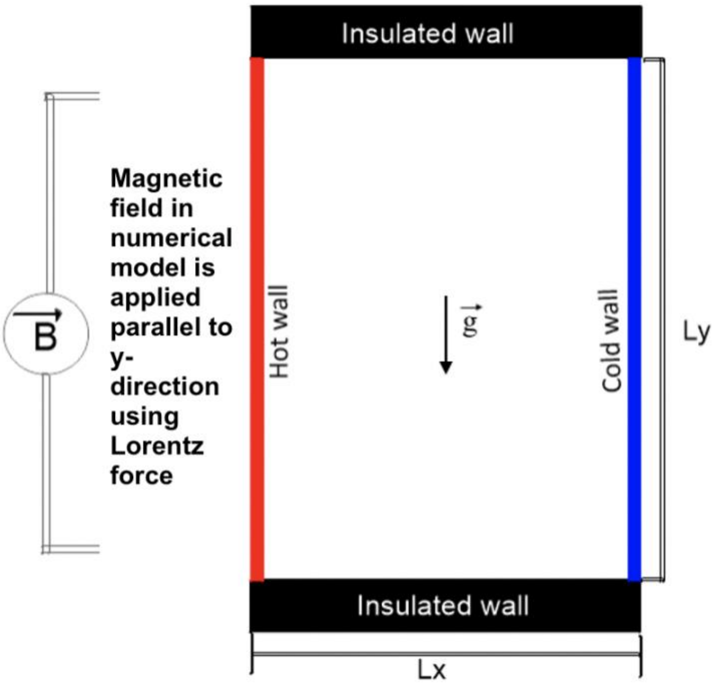

Figure 2*: Schematic Diagram of the model showing the geometry and the boundary conditions*

The continuity (1) and momentum (2) equations are coupled with the energy equation (6). The enthalpy-porosity approach is captured by equations (3) and (4). The Lorentz force in equation (5) is added to the momentum equation (2) to account for the magnetic field.

$$\nabla . \vec{u} = 0 \tag{1}$$

$$\rho \frac{\partial \vec{u}}{\partial \mathrm{t}} + \rho(\vec{u}.\nabla)\vec{u} = -\nabla \mathrm{p} + \mu\nabla^2\vec{u} + \rho\vec{g}\beta\left(T - T_{Ref}\right) + \vec{D} + \vec{F_l} \tag{2}$$

$$\vec{D} = -C\,\frac{(1-\alpha)^2}{\alpha^3+b}\,\vec{u} \tag{3}$$

$$\alpha = \frac{\Delta H}{L} = \begin{cases} 0 & T < T_s \\ \frac{T-Ts}{T_l-T_s} & T_l < T < T_s \\ 1 & T > T_l \end{cases} \tag{4}$$

$$\mathrm{F}_l = \sigma B^2\, u_y \tag{5}$$

$$\rho c_p \frac{\partial \mathrm{T}}{\partial \mathrm{t}} + \rho c_p(\vec{u}.\nabla \mathrm{T}) = \mathrm{k}\nabla^2 T + S \tag{6}$$

$$S = -L\rho\left(\frac{\partial\alpha}{\partial \mathrm{t}} + \nabla.(\alpha\vec{u})\right) \tag{7}$$

where $\boldsymbol{u}$ is the fluid velocity, $\rho$ is the fluid density, $\mu$ is the kinematic viscosity, p is the pressure, $\boldsymbol{D}$ is the Darcy source terms, is the liquid fraction, $C$ is a morphology factor, and $b$ is a value to avoid dividing by zero. $\boldsymbol{F_l}$ is the Lorentz force exerted in the vertical direction, $B$ is the magnetic field strength, $\sigma$ is the electric conductivity of the material, and $u_y$ is the vertical velocity component. For the energy equation (6), $T$ is the temperature, $c_p$ is the specific heat, $k$ is the thermal conductivity and $S$ is the latent heat source term. In solving the energy equation, we use Neuman boundary conditions for the left and right side and Dirichlet boundary conditions for the top and bottom sides with heat flux considered to be zero for the presence of insulation. For the momentum equations, we use no flow boundary conditions for all sides.

The parameters used in the simulation are gathered in Table 1.

| **Parameters** | **Octadecane properties** |
|---|---|
| Density (kg.m$^{-3}$) | 867 (solid), 775.6 (liquid) |
| Latent heat (J.g$^{-1}$) | 243.680 |
| Melting temperature ($^{o}$C) | 28.15 |
| Thermal conductivity (W.m$^{-1}$. K$^{-1}$) | 0.32 (solid), 0.15 (liquid) |
| Specific heat (J. kg$^{1}$. K$^{-1}$) | 1900 (solid), 2240 (liquid) |
| Kinematic viscosity (m$^{2}$.s$^{-1}$) | 4.81 x 10$^{-6}$ |
| Thermal expansion coefficient (K$^{-1}$) | 8.36 x 10$^{-4}$ |

Table 1: *Thermophysical Properties of Octadecane [11]*

# 3. Results and Discussion

## 3.1. Experimental results

To experimentally assess the impact of magnetic field on the melting rate, the plate temperature was maintained at 15$^{o}$C for some time to reach thermal equilibrium. Then the temperature was raised to 40$^{o}$C. The heat flux is measured using the heat flux sensors with sensitivity of 8 mV/(W/cm$^{2}$). The apparent melting rate is then calculated by dividing the energy stored per time (which is the area under the heat flux curve) with the latent heat of fusion. The uncertainty in this case is relative to that of the heat flux reported. Figure 3a shows the evolution of melting fraction with time for the case without and with magnetic field plotted against dimensionless Fourier number ($F_o$). Without magnetic field effect, complete melting occurs at about 795s ($F_o$ = 0.91), while for the case of magnetic field, complete melting occurs at about 1040s ($F_o$ = 1.2). This implies that neodymium magnet of dimension 40mmx15mmx5mm with a magnetic field strength of 240mT can delay the complete melting process for about 245s, which is an increase of about 30% in the melting duration. Similarly, we studied the impact of magnetic field on the rate of solidification of Octadecane. In this case, at the beginning of the experiment, the temperature of the sample was at 40$^{o}$C and then decreased to 15$^{o}$C. Figure 3b shows the evolution of the solid fraction during the solidification process. We observe about 327s (difference of 0.376 in $F_o$), delay for the sample to completely solidify, which constitutes a 17% increase in solidification duration. Hence, applying magnetic field in vertical direction and opposing buoyancy delays melting and solidification.

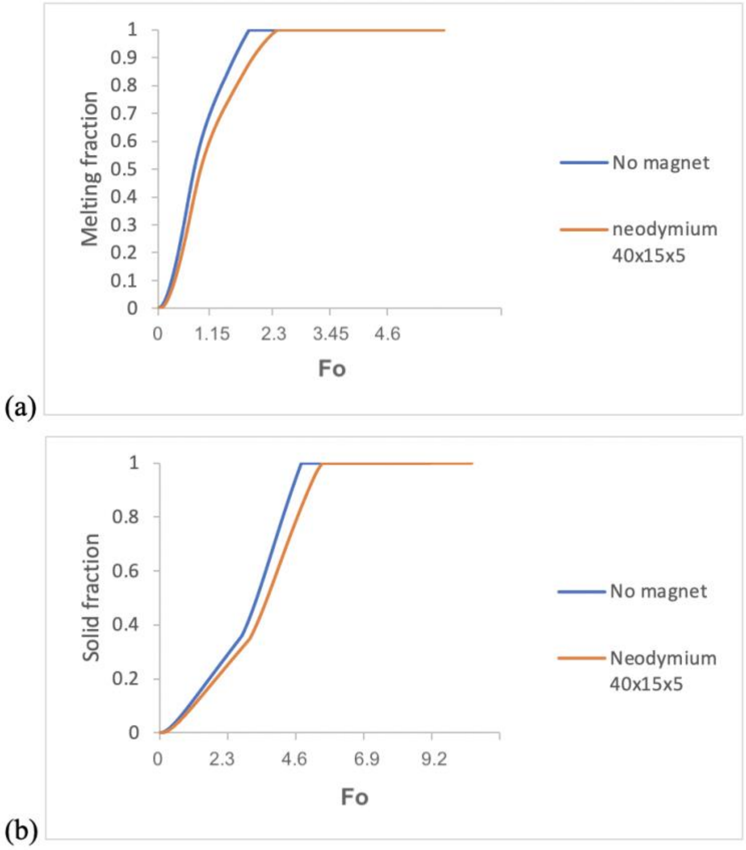

Figure 3: *Evolution of (a) liquid fraction during melting and (b) solid fraction during solidification obtained from the experiment*

### 3.2. Numerical results

To verify the claim that we got experimentally regarding the effect of magnetic field on fusion rates, we use numerical modeling. The effect of magnetic field on the melting process is discussed using the non-dimensional Hartman number 0, 20, 60 and 100. The Hartman number is expressed as,

$$Ha = L_y B \sqrt{\frac{\sigma}{\mu}} \tag{8}$$

The magnetic field can impact the convective flow. This has a corresponding effect on the progression of the melting interface and the rate of melting. Figure 4 shows the average liquid fraction plotted against dimensionless Fourier number ($F_o$). Up to about 1 hour of the simulation time ($F_o = 0.44$), there is no significant effect of the magnetic field on the melting rate. This could be because of the dominant heat transfer mechanism being conduction. As the melting progress and there is increase in convective flow, the effect of magnetic field on the melt fraction can be observed. At the maximum simulation time of 4 hours ($F_o = 1.76$), we notice about 43% decrease in melted fraction at the maximum Hartmann number investigated [12]. We can conclude that higher magnetic field slows the rate of melting if applied in the vertical direction opposing buoyancy. This supports the experimental results although we could not perform an exact comparison as we do not have the electrical characteristics of the magnet to estimate the Hartman number.

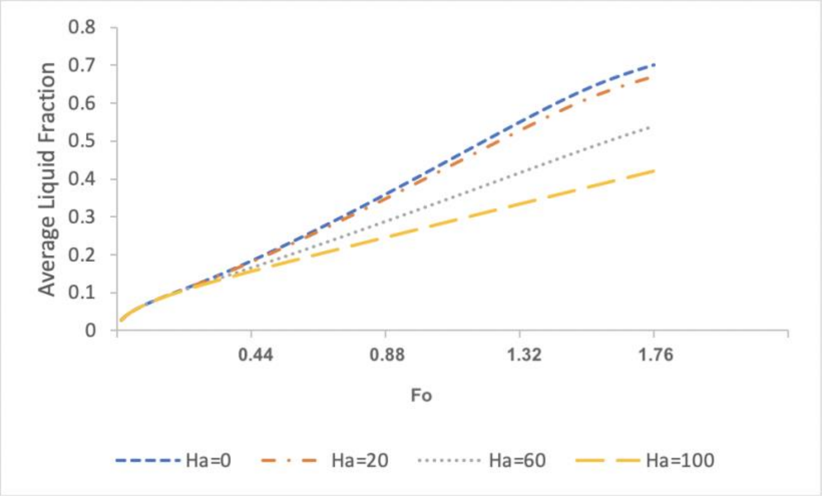

Figure 4: *Average liquid fraction obtained from the numerical model versus time plotted for various Hartmann numbers*

## 4. Conclusion

For an efficient performance of phase-change materials (PCM)s in thermal energy storage systems, the time needed for the phase-change process should be well coordinated with the duration of external heating and cooling. Thus, it is important to investigate methods to control the melting of PCMs. In this work, we investigated how magnetic field affects the fusion rates of Octadecane. The results can open the door for designing systems where the PCM fusion is controlled depending on the expected external heating and cooling rates.

The effect of magnetic field on the melting of PCMs depends on the magnitude of the field, the PCM properties, and the enclosure geometry. This is inferred from the decrease in rate of melting as the Hartman number increases, up to 43% for the maximum investigated magnetic field when Lorentz force is directed opposite to the buoyant force. This is further confirmed by the experimental results. As the magnitude of the magnetic field applied on the vertical side of the enclosure increases, the rate of melting decreases and this becomes more evident as the melting front proceeds and as convection's contribution becomes stronger.

## References

[1] International Energy Agency, "*Global Energy Review 2021,*", pp. 1-36, 2021.

[2] E. Katramiz, H. al Jebaei, S. Alotaibi, W. Chakroun, N. Ghaddar, and K. Ghali, "Sustainable cooling system for Kuwait hot climate combining diurnal radiative cooling and indirect evaporative cooling system," *Energy*, vol. 213, 2020. https://doi.org/10.1016/j.energy.2020.119045

[3] R. Aridi and A. Yehya, "Review on the sustainability of phase-change materials used in buildings," *Energy Conversion and Management: X*, vol. 15, 100237. https://doi.org/10.1016/j.ecmx.2022.100237

[4] Q. Meng and J. Hu, "A poly (ethylene glycol)-based smart phase change material," *Solar Energy Materials and Solar Cells*, vol. 92(10), pp. 1260-1268, 2008. https://doi.org/10.1016/j.solmat.2008.04.026

[5] A. Yehya, H. Naji, and L. Zalewski, "Experimental and numerical characterization of an impure phase change material using a thermal lattice Boltzmann method," *Appl. Therm. Eng.*, vol. 154, no. 2018, pp. 738-750, 2019. https://doi.org/10.1016/j.applthermaleng.2019.03.026.

[6] M. Dannemand, J. M. Schultz, J. B. Johansen, and S. Furbo, "Long term thermal energy storage with stable supercooled sodium acetate trihydrate," *Appl. Therm. Eng.*, vol. 91, pp. 671-678, 2015. https://doi.org/10.1016/j.applthermaleng.2015.08.055

[7] A. Hasan, S. J. McCormack, M. J. Huang, and B. Norton, "Energy and cost saving of a photovoltaic-phase change materials (PV-PCM) System through temperature regulation and performance enhancement of photovoltaics," *Energies*, vol. 7(3), pp. 1318-1331, 2014. https://doi.org/10.3390/en7031318

[8] S. Wijesuriya, P. C. Tabares-Velasco, K. Biswas, and D. Heim, "Empirical validation and comparison of PCM modeling algorithms commonly used in building energy and hygrothermal software," *Building and Environment*, vol. 173, no. February, p. 106750, 2020, https://doi.org/10.1016/j.buildenv.2020.106750

[9] N. Gan Jia Gui, C. Stanley, N. T. Nguyen, and G. Rosengarten, "Ferrofluids for heat transfer enhancement under an external magnetic field," *Int. J. Heat and Mass Transfer*, vol. 123, pp. 110–121, 2018, https://doi.org/10.1016/j.ijheatmasstransfer.2018.02.100

[10] A. Doostani, M. Ghalambaz, and A. J. Chamkha, "MHD natural convection phase-change heat transfer in a cavity: analysis of the magnetic field effect," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 39, no. 7, pp. 2831–2846, 2017, https://doi.org/10.1007/s40430-017-0722-z

[11] D. Nakhla, E. Thompson, B. Lacroix, and J. S. Cotton, "Measurement of heat transfer enhancement in melting of n-Octadecane under gravitational and electrohydrodynamics (EHD) forces," *Journal of Electrostatics*, vol. 92, no. January, pp. 31–37, 2018, https://doi.org/10.1016/j.elstat.2018.01.004

[12] P. Adebayo and A. Yehya. The effect of combining magnetic field and high-conductivity nanoparticles on the fusion rate of a phase change material. *Energy Conversion and Management* : X 16 (2022) 100314. https://doi.org/10.1016/j.ecmx.2022.100314