

Received: 08/07/2026

Accepted: 10/08/2026

Published: 24/09/2026

Citation: Goudo Y, Djaglo AKA, Adanlété AA (2026) Effect of Magnetic Field Orientation on Thermal Conductivity in FeNi₂ Alloys. Indian Journal of Science and Technology 19(34): 2384-2391. <https://doi.org/10.17485/IJST/v19i34.1027>

* **Corresponding author.**

jonathangoudo2@gmail.com

Funding: None

Competing Interests: None

Copyright: © 2026 Goudo et al. This is an open access article distributed under the terms of the [Creative Commons Attribution License](#), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Published By Indian Society for Education and Environment ([iSee](#))

ISSN

Print: 0974-6846

Electronic: 0974-5645

Effect of Magnetic Field Orientation on Thermal Conductivity in FeNi₂ Alloys

Yogoubé Goudo^{1*}, Anani Koffi Ayélété Djaglo², AA Adanlété²

¹ Université de Lomé, Facultés Des Sciences, Département de Physique, Laboratoire de Physique des Matériaux et des Composants à Semi-conducteurs (LPMCS), B.P 1515 Lomé - Togo

² Université de Kara, Faculté des Sciences et Techniques, Département de Physique, Laboratoire Matériaux, Energies Renouvelables et Environnement (LaMERE), B.P 404 Kara - Togo

Abstract

Objectives: This study aims to quantify how the orientation of an external magnetic field influences the thermal conductivity of FeNi₂ (permalloy) alloys.

Method: This study used a multiscale approach combining LAMMPS spin-lattice dynamics simulations and analytical calculations to investigate heat transport under different magnetic-field orientations. **Findings:** Simulations reveal a strong angular dependence in the thermal conductivity $\kappa(\theta)$. At 400 K, an enhancement of approximately 23% in thermal conductivity was observed when the heat flux is parallel to the magnetic field ($\theta = 0^\circ$); whereas, a reduction of nearly 19% occurs for the perpendicular configuration ($\theta = 90^\circ$). For ($\theta = 45^\circ$), the thermal conductivity remains nearly identical to that of the non-magnetic state. At this specific angle, the overall magnetothermal anisotropy is reduced due to a partial compensation between spin-dependent scattering mechanisms, which include spin-phonon interactions, magnon-related scattering, as well as spin-orbit coupling (SOC). **Novelty:** Unlike previous studies that mainly focused on the effect of magnetic-field intensity, this work demonstrates that the field orientation alone can be used to tune heat transport in FeNi₂ alloys. The identification of a characteristic angle at which the thermal conductivity approaches its non-magnetic value provides new insight into the directional control of thermal transport in ferromagnetic materials.

Keywords: Thermal conduction; Magnetic field; Heat flux; FeNi₂ alloys

1 Introduction

Thermal transport in ferromagnetic materials has attracted increasing attention because of its importance for spin caloritronics, thermal management, and energy-conversion technologies^{(1), (2), (3), (4), (5)}. Unlike conventional metals, heat in ferromagnets is transported by three interacting energy carriers: electrons, phonons, and magnons. In the literature, recent experimental and theoretical studies have shown that spin-dependent scattering, spin-phonon interactions, and spin-orbit coupling (SOC)

strongly influence the thermal conductivity, particularly near the Curie temperature or under an applied magnetic field^{(4),(6),(7),(8),(9)}. These advances have improved the understanding of heat transport in ferromagnetic materials and have opened new possibilities to control thermal conduction through magnetic order.

Applying an external magnetic field modifies the magnetic configuration of a ferromagnet by aligning the magnetic moments and reducing domain-wall disorder⁽¹⁰⁾. This magnetic reorganization changes the scattering experienced by electrons, phonons, and magnons, making thermal conductivity dependent on the orientation of the heat flux with respect to the magnetic field^{(2),(4),(7),(8)}. Consequently, magnetothermal anisotropy has emerged as an important mechanism for controlling heat transport in magnetic materials. Although the influence of magnetic fields on thermal transport has been widely investigated, most previous studies have focused on magnetic-field intensity, magnetic phase transitions, or domain-wall effects^{(11),(12),(13)}. Much less attention has been paid to the angular dependence of thermal conductivity in bulk FeNi alloys^{(10),(14),(15),(16)}. In particular, it remains unclear whether a specific orientation of the magnetic field can compensate for magnetothermal anisotropy and make the thermal conductivity approach that of the non-magnetic state. Addressing this question is essential for the design of magnetic materials with controllable thermal transport properties.

To address this issue, this study investigates the influence of the angle between the applied magnetic field and the heat flux on the thermal conductivity of FeNi₂ alloys. Spin-lattice dynamics simulations performed with LAMMPS are combined with an analytical model based on the Wiedemann-Franz law and anisotropic magnetoresistance (AMR) theory to quantify the angular variation of thermal conductivity and validate the numerical predictions. Particular attention is paid to identifying the characteristic angle at which the thermal conductivity becomes nearly identical to that of the non-magnetic state.

Unlike previous studies that mainly considered the influence of magnetic-field strength, the present work demonstrates that the field orientation itself provides an effective means of tuning thermal conductivity. The identification of a characteristic angle at which magnetothermal anisotropy is largely compensated constitutes the main contribution of this work and provides new insight into the directional control of heat transport in ferromagnetic alloys.

2 Methodology

2.1 Spin-lattice Hamiltonian

The total energy of a ferromagnetic system (the total Hamiltonian) can be expressed as the sum of the contributions associated with each heat carrier, namely electrons ($\mathcal{H}_e$), phonons ($\mathcal{H}_l$) and magnons ($\mathcal{H}_s$), together with their mutual interactions $\mathcal{H}_{e-s}$ and $\mathcal{H}_{s-l}$:

$$\mathcal{H} = \mathcal{H}_e + \mathcal{H}_l + \mathcal{H}_s + \mathcal{H}_{e-s} + \mathcal{H}_{s-l} \quad (1)$$

In a spin-lattice dynamics simulation framework, the total energy is reduced to:

$$\mathcal{H} = \mathcal{H}_l + \mathcal{H}_s + \mathcal{H}_{s-l} \quad (2)$$

The spin-spin exchange interactions (J_{ij}) and spin-lattice interactions ($J(r_{ij})$) used to model the spin Hamiltonian are of comparable magnitude. These parameters are obtained from Density Functional Theory (DFT) calculations⁽⁶⁾, with values ranging from approximately 17.3 to 24.4 meV depending on the nickel concentration within the alloy. The interaction potentials used for the lattice Hamiltonian are based on Embedded Atom Method (EAM) potentials developed for FeNi alloys by Zhou *et al.*^{(17),(18)}.

The spin dynamics is governed by the Landau–Lifshitz–Gilbert (LLG) equation:

$$\frac{dS_i}{dt} = -\gamma S_i \times H_{eff} + \alpha S_i \times \frac{dS_i}{dt} \quad (3)$$

Where S_i represents the spin vector of atom i , H_{eff} is the effective magnetic field and α is the Gilbert damping. In this equation, we added the Zeeman term associated with the saturating external magnetic field $\vec{B}$, leading to the alignment of magnetic moments along the magnetic field direction:

$$E_Z = -\mu_S \sum \vec{S}_i \cdot \vec{B} \quad (4)$$

2.2 Simulation Method: Green-Kubo calculations.

The thermal conductivity is calculated using the Green-Kubo formalism through the heat flux autocorrelation function:

$$\kappa = \frac{1}{k_B T V} \int_0^{+\infty} \langle \varphi(0) \varphi(t) \rangle dt \quad (5)$$

where φ represents the heat flux, T is the temperature, V the system volume, and k_B denotes the Boltzmann constant.

For the simulations, a bulk FeNi_2 structure with dimensions of $100 \text{ nm} \times 10 \text{ nm} \times 10 \text{ nm}$ was considered to ensure that the phonon and magnon mean free paths relevant to thermal transport are adequately represented⁽⁶⁾. The lattice parameter was set to $a=0.355 \text{ nm}$, corresponding to an approximate total number of 10^6 atoms. Periodic boundary conditions were applied along the three spatial directions. Our simulations were carried out with a time step of 0.5 fs over a total simulation duration of 100 ps , in line with our previous work on the same alloy⁽⁶⁾. A sufficiently strong magnetic field ($B=2 \text{ T}$) was applied in order to ensure magnetic saturation of the material. Using the compute heat flux command implemented in LAMMPS⁽¹⁹⁾, the heat flux component φ_x along the (Ox) direction was evaluated. The different simulation configurations considered in this study are summarized in Table 1. For each configuration, a set of five independent simulations was performed under identical conditions, and the reported thermal conductivity values correspond to the averaged results obtained from these simulations.

Table 1. Different orientations of the applied magnetic field and corresponding calculated thermal conductivity values (κ)

Angle θ	Applied Magnetic Field B	Heat Flux Used	Obtained Thermal Conductivity
-	$B = 0$	φ_X	κ_0
0°	$B = (B, 0, 0)$	φ_X	$\kappa_{\parallel}$
30°	$B = (B\cos 30^\circ, B\sin 30^\circ, 0)$	φ_X	κ_{30°
45°	$B = (B\cos 45^\circ, B\sin 45^\circ, 0)$	φ_X	κ_{45°
60°	$B = (B\cos 60^\circ, B\sin 60^\circ, 0)$	φ_X	κ_{60°
90°	$B = (0, B, 0)$	φ_X	$\kappa_{\perp}$

2.3 Analytical Model – Wiedemann–Franz Law and AMR

The total thermal conductivity κ of a ferromagnetic material results from the combined contributions of the three main heat carriers: electrons (κ_e), phonons (κ_{ph}), and magnons (κ_{mag}).

$$\kappa = \kappa_e + \kappa_{ph} + \kappa_{mag} \quad (6)$$

For ferromagnetic metals such as permalloy, the electronic contribution largely dominates: $\kappa_e \gg \kappa_{ph}, \kappa_{mag}$, therefore, the approximation $\kappa_e = \frac{2}{3}\kappa$ can be reasonably applied⁽⁶⁾.

The Wiedemann–Franz (WF) law used to estimate the electronic thermal conductivity is expressed as:

$$\kappa_e = L_0 \sigma T \quad (7)$$

Or equivalently:

$$\kappa_e = \frac{L_0 T}{\rho} \quad (8)$$

where L_0 denotes the Lorenz constant, T is the temperature, while σ and ρ represent the electrical conductivity and electrical resistivity of the material, respectively.

The AMR effect in a ferromagnetic material refers to the dependence of the electrical resistance on the angle between the electric current density vector and the magnetization direction. This phenomenon originates from spin-orbit coupling and anisotropic scattering of conduction electrons. The angular dependence of the electrical resistivity is given by:

$$\rho(\theta) = \rho_{\perp} + (\rho_{\parallel} - \rho_{\perp}) \cos^2 \theta \quad (9)$$

where $\rho_{\perp}$ and $\rho_{\parallel}$ correspond to the electrical resistivities measured when the magnetization is perpendicular and parallel to the current direction, respectively.

For FeNi_2 permalloy, experimental values of $\rho_{\perp}$ and $\rho_{\parallel}$ reported in the literature allow the calculation of $\rho(\theta)$ ^{(20), (21), (22), (23)}. This angular-dependent resistivity can then be introduced into the Wiedemann–Franz relation to evaluate the variation of the electronic thermal conductivity as a function of the magnetic field orientation:

$$\kappa_e(\theta) = \frac{L_0 T}{\rho(\theta)} \quad (10)$$

Thus, at 300 K , the calculated values of the electronic thermal conductivity are respectively: $\kappa_e^{\perp} = 14.4 \text{ W.m}^{-1}.\text{K}^{-1}$ and $\kappa_e^{\parallel} = 12.7 \text{ W.m}^{-1}.\text{K}^{-1}$.

3 Results and Discussion

3.1 Model Validation and Temperature Dependence

We performed spin-lattice dynamics simulations implemented in LAMMPS to evaluate the thermal conductivity κ of FeNi₂ alloys. To establish the validity of our computational approach, we first compared our baseline non-magnetic thermal conductivity at 400 K ($\kappa_0 = 16.35 \text{ W.m}^{-1}.\text{K}^{-1}$) with existing literature^{(6), (24), (25)}. Our predicted value is in excellent quantitative agreement with recent experimental measurements on structurally similar Fe-Ni alloys^{(6), (24)}, which report room-to-mid-temperature thermal conductivities in the range of $14 - 18 \text{ W.m}^{-1}.\text{K}^{-1}$ ^{(6), (25)}. Furthermore, our baseline closely matches recent computational studies utilizing first-principles density functional theory and Boltzmann transport equations⁽²⁶⁾. The consistency between our spin-lattice dynamics predictions and these previously reported results demonstrates that our LAMMPS model accurately captures the fundamental lattice dynamics and intrinsic scattering rates of the alloy prior to the application of a saturating magnetic field.

When investigating the temperature dependence under varying magnetic field orientations, we observed a progressive decrease in thermal conductivity across all angular configurations as the temperature increased (Figure 1). This behavior aligns with the classical theory of thermal transport in ferromagnetic metals^{(24), (27)}. As the lattice temperature rises, the population of both phonons and magnons (spin waves) increases significantly. Consequently, the mean free path of our primary heat carriers is reduced due to intensified high-momentum Umklapp scattering, alongside enhanced electron-magnon and spin-phonon interactions. The thermal agitation acts as a dense background of scattering centers, inherently increasing the thermal resistance of the FeNi₂ lattice.

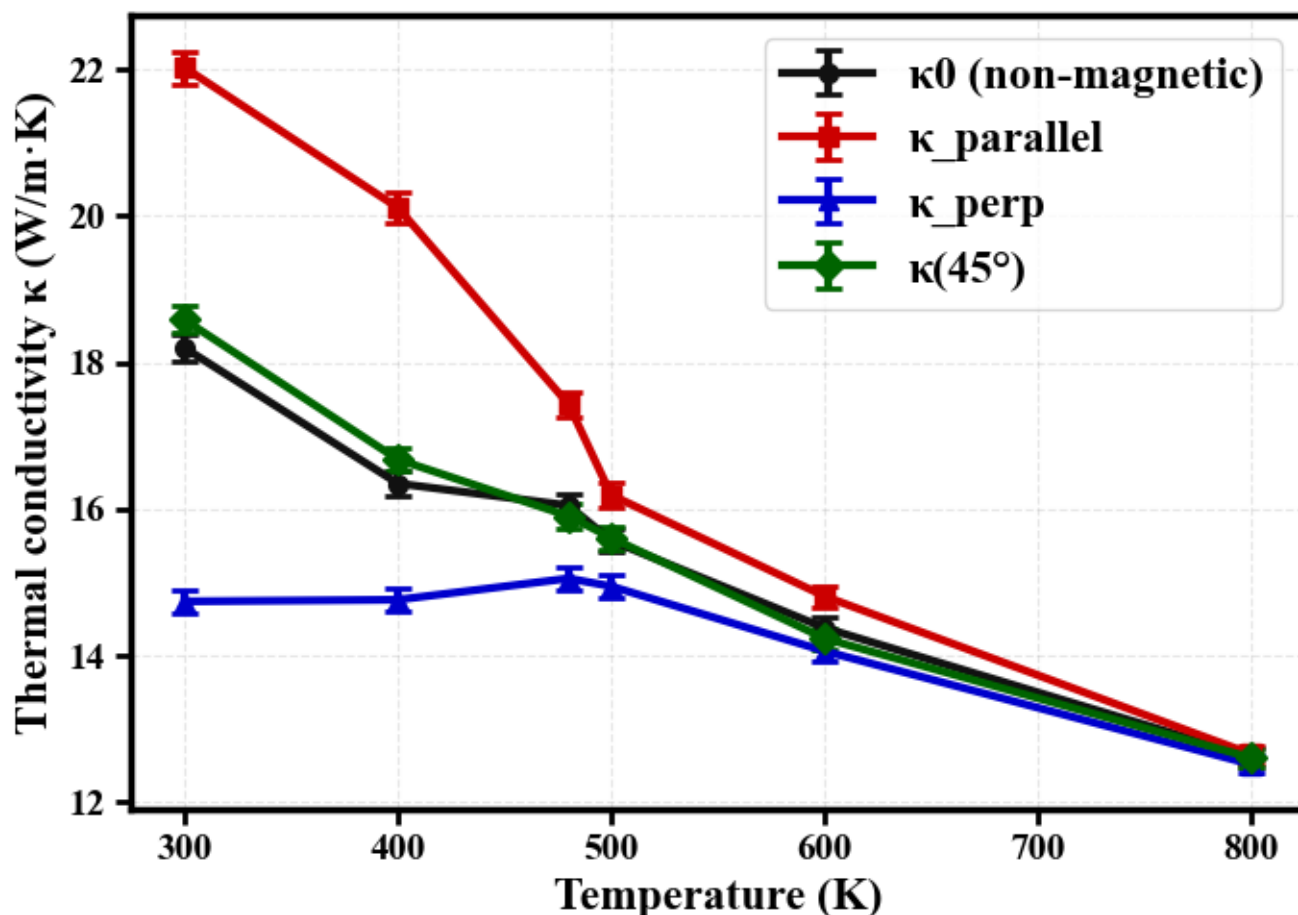


Fig 1. Variation of the thermal conductivity of FeNi₂ for different orientations of the applied magnetic field. Error bars represent the standard deviation calculated from five independent simulations.

Importantly, our simulations reveal that as the temperature approaches 800 K, the distinct $\kappa(\theta)$ curves progressively converge toward a single common value. From a thermodynamic perspective, this convergence reflects the thermal energy ($k_B T$) overcoming the local magnetic exchange energy. As the system approaches the Curie temperature, massive random thermal fluctuations disrupt the local ferromagnetic ordering. Consequently, the heat carriers experience a magnetically disordered lattice regardless of the external field orientation. In this paramagnetic-like limit, the spin-dependent scattering cross-section is spatially averaged, yielding a fully isotropic thermal transport regime where $\kappa(0^\circ) \approx \kappa(45^\circ) \approx \kappa(90^\circ)$.

3.2 Magnetothermal Anisotropy and Field Orientation

At lower temperatures, our results reveal a pronounced anisotropy in thermal conductivity, validated by the presence of Anisotropic Magnetothermal Resistance (AMTR) in our simulated alloy. When we applied the magnetic field parallel to the heat flux direction ($\theta = 0^\circ$), the thermal conductivity reached its maximum value. Specifically, at 400 K, we obtained $\kappa = 20.11 \text{ W.m}^{-1}.\text{K}^{-1}$, which corresponds to an enhancement of approximately 23% compared to our non-magnetic baseline. This enhancement originates from the alignment of magnetic moments along the transport direction, reducing spin-dependent scattering and effectively lengthening the mean free path. The magnitude of this enhancement is consistent with similar trends reported in recent transport studies on highly spin-polarized ferromagnetic materials^{(10), (14), (21)}. In sharp contrast, when the field was applied perpendicularly to the heat flux ($\theta = 90^\circ$), our calculated thermal conductivity dropped to $\kappa = 14.76 \text{ W.m}^{-1}.\text{K}^{-1}$, which represents a 19% reduction at 400 K. In this transverse geometry, conduction electrons are forced to propagate across the spin texture imposed by the field, which enhances spin-dependent scattering processes and limits the relaxation time.

Finally, in the inclined configuration ($\theta = 45^\circ$), we found that the thermal conductivity closely mimics the non-magnetic state (κ_0) across a wide temperature range. To understand this behavior, one must analyze the angular dependence of the scattering tensor components. Phenomenologically, the AMTR in transition-metal alloys follows a characteristic $\cos^2 \theta$ dependence, expressed in Equation 9. At the specific angle of ($\theta = 45^\circ$), the geometric projections yield $\cos^2(45^\circ) = \sin^2(45^\circ) = 0.5$, meaning that the effective thermal conductivity represents the exact arithmetic mean of the two extreme transport regimes.

To understand the fundamental microscopic origins of these varying scattering rates across all three orientations, we must examine the role of spin-orbit coupling (SOC) within Mott's s - d scattering framework. In our FeNi₂ model, heat is primarily transported by highly mobile $4s$ conduction electrons that frequently scatter into heavier, localized $3d$ states. The SOC links the spatial orientation of these $3d$ orbitals to the direction of the local magnetization. For the parallel orientation, the field-aligned magnetization deforms those $3d$ orbitals, which presents a minimized scattering cross-section to the traveling $4s$ electrons. Conversely, for the perpendicular orientation, our modeled carriers face a maximized orbital scattering cross-section. Furthermore, propagating transversely exposes the electrons to stronger interactions with non-collinear magnons and transverse spin fluctuations. At $\theta = 45^\circ$, the heat carriers (electrons and phonons) propagate at an angle where the longitudinal spin-coherence effects, which tend to minimize s - d scattering and enhance the mean free path at $\theta = 0^\circ$, are perfectly counterbalanced by the transverse orbital scattering cross-sections and magnon-induced diffusion processes that maximize thermal resistance at $\theta = 90^\circ$. Because the enhancement factor (parallel alignment) and the reduction factor (perpendicular texture) possess nearly symmetrical magnitudes relative to the unperturbed lattice, their simultaneous activation at 45° cancels out their net macroscopic effect. Quantitatively, the average orientation of the conductivity tensor for a macroscopically isotropic magnetic configuration is given by⁽²⁸⁾:

$$\kappa_{iso} = \frac{1}{3}\kappa_{\parallel} + \frac{2}{3}\kappa_{\perp} \quad (11)$$

Using the conductivities calculated at 400 K, we obtain: $\kappa_{iso} = 16.54 \text{ W.m}^{-1}.\text{K}^{-1}$, which is very close to the Green-Kubo value obtained for the non-magnetic state. Consequently, the net magnetic contribution to the thermal transport tensor vanishes, forcing the system to mimic an isotropic, non-magnetic-like transport regime^{(2), (10), (14)}.

Given that the Green-Kubo calculations are sensitive to the integration time, Figure 2 shows the convergence plots, which demonstrate the reliability of the results obtained.

3.3 Validation Using the Analytical Model

To validate the spin-lattice dynamics simulations, an analytical approach combining the Wiedemann–Franz (WF) law and the theory of Anisotropic Magnetoresistance (AMR) was employed. According to the classical two-current model developed by Campbell, Fert, and Jaoul^{(29), (30)}, the anisotropic transport in transition-metal alloys is governed by spin-orbit coupling. This coupling induces an asymmetry in the s - d scattering cross-section of the conduction electrons depending on the relative angle

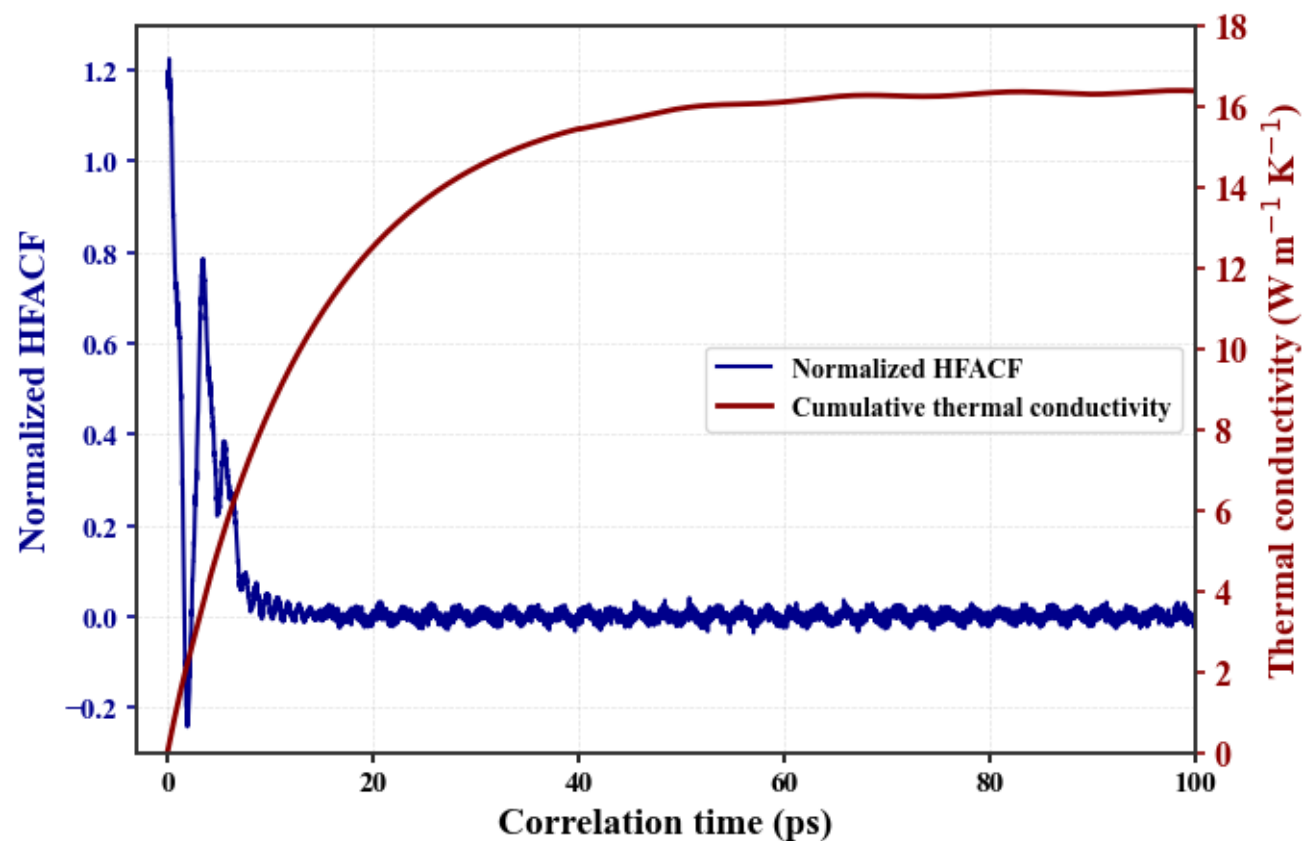


Fig 2. Convergence curve for Green-Kubo calculations

θ between the current density and the local magnetization. By extending this electrical principle to thermal transport via the WF law, the electronic thermal conductivity inherently adopts the characteristic angular dependence of the AMR. At 300 K, substituting the experimental resistivity values of FeNi₂ into this analytical relation yields an electronic thermal conductivity κ_e that accounts for approximately two-thirds of the total thermal conductivity κ_{total} obtained from our LAMMPS simulations. Table 2 provides a comparative and quantitative summary of our results alongside those of recent studies. This quantitative ratio ($\sim 66\%$) is in excellent agreement with theoretical expectations for metallic ferromagnets, where electrons dominate heat transport, but phonons and magnons provide a non-negligible secondary contribution. Therefore, the analytical model not only confirms the correct order of magnitude of the LAMMPS results but also proves that the angular modulation observed in the simulations is fundamentally rooted in the spin-orbit-induced anisotropic scattering mechanisms.

Table 2. Quantitative comparison of the results obtained

Reference	Material	Method	Temperature (K)	Thermal conductivity (W m ⁻¹ K ⁻¹)
Present work	FeNi ₂	Spin-lattice dynamics (LAMMPS)	400	16.35
Goudo et al. (2025) ⁽⁶⁾	FeNi ₂	NEMD method	300 – 410	14 -18
Sahoo et al. (2025) ⁽¹⁴⁾	FeNi alloys	Experimental	300 – 500	15 – 20
Ma et al. (2023) ⁽²⁶⁾	3d ferromagnets	DFT + Boltzmann transport	300	Comparable electronic contribution
Khadzhay et al. (2020) ⁽²³⁾	FeNi	Experimental	Low temperature	Consistent electronic conductivity

4 Conclusion

This work investigated an aspect of anisotropic heat transport that has received comparatively little attention in transition-metal alloys. By combining spin-lattice dynamics simulations in LAMMPS with an analytical model based on the Wiedemann-Franz law and anisotropic magnetoresistance (AMR) theory, we established a direct relationship between magnetic-field orientation and thermal conductivity in ferromagnetic FeNi₂ alloys. The simulations reveal a pronounced magnetothermal anisotropy throughout the investigated temperature range. At 400 K, the thermal conductivity increases by approximately 23% when the magnetic field is parallel to the heat flux and decreases by about 19% in the perpendicular configuration. The most significant result is the identification of a characteristic angle of 45°, at which the thermal conductivity becomes nearly identical to that of the non-magnetic state owing to the partial compensation between spin-orbit-coupling-induced anisotropic scattering, spin-phonon interactions, and magnon-related scattering. The consistency between the numerical predictions, the analytical model, and previously reported trends supports the validity of the proposed spin-lattice dynamics approach. More importantly, this study demonstrates that the orientation of an external magnetic field can be used as an additional parameter to tailor heat transport without changing either the material composition or the magnetic-field strength. These findings provide new insight into magnetothermal anisotropy and offer promising perspectives for spin-caloritronic devices, thermomagnetic energy converters, and advanced thermal-management technologies. Future work will focus on extending this approach to other ferromagnetic materials and on experimentally validating the predicted angular dependence, potentially utilizing time-domain thermoreflectance (TDTR) on oriented single-crystal FeNi₂ samples under variable magnetic fields.

References

- 1) Afeniyevh SDM, Adjanoh AA, Douti DBL, Pakam T. Thermal simulation and optimization of a Curie-based thermomagnetic motor harnessing concentrated solar energy. *AIP Advances*. 2024;14(2):025221. <https://doi.org/10.1063/5.0182779>.
- 2) ichi Uchida K, Hirai T. Spin caloritronics: history and future prospects of experiments. *Journal of Magnetism and Magnetic Materials*. 2026;652:174195. <https://doi.org/10.1016/j.jmmm.2026.174195>.
- 3) ichi Uchida K, Sakuraba Y, Sepehri-Amin H. Foreword to the focus issue: materials science and technology for magnetic thermal management. *Science and Technology of Advanced Materials*. 2025;26(1):2604891. <https://doi.org/10.1080/14686996.2025.2604891>.
- 4) Yang G, Sang L, Zhang C, Ye N, Hamilton A, Fuhrer MS, et al. The role of spin in thermoelectricity. *Nature Reviews Physics*. 2023;5(8):466–482. <https://doi.org/10.1038/s42254-023-00604-0>.
- 5) Elahi E, Al-Kahtani AA, Dastgeer G, Aftab S, Aziz J, Iqbal MW, et al. Recent advances in thermomagnetic devices for spin-caloritronic phenomena. *Applied Materials Today*. 2023;32:101846. <https://doi.org/10.1016/j.apmt.2023.101846>.
- 6) Goudo Y, Adjanoh AA, Afeniyevh SDM. Impact of spin waves on thermal conduction in pure FeNi alloys. *Journal of Alloys and Compounds*. 2025;1048:185298. <https://doi.org/10.1016/j.jallcom.2025.185298>.
- 7) Hirai T, Morita T, Biswas S, Uzuhashi J, Yagi T, Yamashita Y, et al. Non-Equilibrium Magnon Engineering Enabling Significant Thermal Transport Modulation. *Advanced Functional Materials*. 2025;35(40):2506554. <https://doi.org/10.1002/adfm.202506554>.
- 8) Wang K, Ren K, Hou Y, Cheng Y, Zhang G. Magnon-phonon coupling: from fundamental physics to applications. *Physical Chemistry Chemical Physics*. 2023;25(33):21802–21815. <https://doi.org/10.1039/d3cp02683c>.
- 9) Nikolov S, Tranchida J, Ramakrishna K, Lokamani M, Cangi A, Wood MA. Dissociating the phononic, magnetic and electronic contributions to thermal conductivity: a computational study in alpha-iron. *Journal of Materials Science*. 2022;57(23):10535–10548. <https://doi.org/10.1007/s10853-021-06865-3>.
- 10) Inosov DS, Onykiienko YO, Tymoshenko YV, Akopyan A, Shukla D, Prasai N, et al. Magnetic-field dependence of low-energy magnons, anisotropic heat conduction, and spontaneous relaxation of magnetic domains in the cubic helimagnet ZnCr₂Se₄. *Physical Review B*. 2020;102(18):184431. <https://doi.org/10.1103/PhysRevB.102.184431>.
- 11) Younes A, Amraoui R, Amar H, Abada A, Manseri A. Magnetic and structural behaviour of Ni₃Fe/NiFe₂O₄/ZnFe₂O₄ nanocomposites synthesized via mechanical alloying. *Bulletin of Materials Science*. 2025;48(4):134. <https://doi.org/10.1007/s12034-025-03501-7>.
- 12) Abada A, Younes A, Abada O, Amraoui R. Correction to: Magnetic and Structural Properties of Nanostructured FeNi and FeSn Synthesized via Powder Metallurgy Process. *Transactions of the Indian Institute of Metals*. 2025;79(1):13. <https://doi.org/10.1007/s12666-025-03758-w>.
- 13) Younes A, Bouamer A, Amraoui R, Metidji N, Guessoum M, Abada A. Magnetic and Structural Properties of Fe-Ni and Fe-Ni-Gr Based Nanostructured Alloys Synthesized by Mechanical Alloying. *Journal of Nano Research*. 2023;78:1–16. <https://doi.org/10.4028/p-5b903c>.
- 14) Sahoo A, Biswal AA, Parida SK, Medicherla VRR, Behera SS, Singh MN, et al. Electronic, magnetic and thermal behavior near the Invar compositions of Fe-Ni alloys. *Journal of Electron Spectroscopy and Related Phenomena*. 2025;280:147540. <https://doi.org/10.1016/j.elspec.2025.147540>.
- 15) Zhang D, Wang K, Chen S, Zhang L, Ni Y, Zhang G. Regulating the thermal conductivity of monolayer MnPS₃ by a magnetic phase transition. *Nanoscale*. 2023;15(3):1180–1185. <https://doi.org/10.1039/d2nr04709h>.
- 16) Bajaj N, Roy AP, Khandelwal A, Chattopadhyay MK, Sathe V, Mishra SK, et al. Magnetoelastic coupling and spin contributions to entropy and thermal transport in biferroic yttrium orthochromite. *Journal of Physics: Condensed Matter*. 2021;33(12):125702. <https://doi.org/10.1088/1361-648X/abd781>.
- 17) Farkas D, Caro A. Model interatomic potentials for Fe–Ni–Cr–Co–Al high-entropy alloys. *Journal of Materials Research*. 2020;35(22):3031–3040. <https://doi.org/10.1557/jmr.2020.294>.
- 18) Mahata A, Mukhopadhyay T, Zaeem MA. Modified embedded-atom method interatomic potentials for Al–Cu, Al–Fe and Al–Ni binary alloys: From room temperature to melting point. *Computational Materials Science*. 2022;201:110902. <https://doi.org/10.1016/j.commatsci.2021.110902>.
- 19) Surblys D, Matsubara H, Kikugawa G, Ohara T. Methodology and meaning of computing heat flux via atomic stress in systems with constraint dynamics. *Journal of Applied Physics*. 2021;130(21):215104. <https://doi.org/10.1063/5.0070930>.
- 20) University SS, Bezdidko OV, Shkurdoda YO, Shpetnyi IO. Electrical Conductivity and Magnetoresistive Properties of Film Alloys Based on Permalloy Fe_{0.5}Ni_{0.5} and Copper. *Journal of Nano-Electronics and Physics*. 2020;12(3):03034–1–03034–4. [https://doi.org/10.21272/jnep.12\(3\).03034](https://doi.org/10.21272/jnep.12(3).03034).

- 21) Zeng FL, Ren ZY, Li Y, Zeng JY, Jia MW, Miao J, et al. Intrinsic Mechanism for Anisotropic Magnetoresistance and Experimental Confirmation in $\text{Co}_x\text{Fe}_{1-x}$ Single-Crystal Films. *Physical Review Letters*. 2020;125(9):097201. <https://doi.org/10.1103/PhysRevLett.125.097201>.
- 22) Kateb M, Ingvarsson S. Correlation of uniaxial magnetic anisotropy axes and principal resistivities in polycrystalline ferromagnetic films. *Journal of Magnetism and Magnetic Materials*. 2021;532:167982. <https://doi.org/10.1016/j.jmmm.2021.167982>.
- 23) Khadzhay GY, Vovk SR, Vovk RV, Gevorkyan ES, Zubenko NS, Kislitsa MV, et al. Electrical and thermal conductivity of FeNi at low temperatures. *Low Temperature Physics*. 2020;46(9):939–943. <https://doi.org/10.1063/10.0001717>.
- 24) Ney V, Lenz K, Ganss F, Hübner R, Lindner J, Ney A. Temperature dependence of bulk and interface contributions to the magnetic damping of Permalloy thin films. *Physical Review Materials*. 2026;10(2):024409. <https://doi.org/10.1103/61vn-39dq>.
- 25) Li WJ, Li Z, He XT, Wang C, Zhang P. Constraints on the thermal evolution of Earth's core from ab initio calculated transport properties of FeNi liquids. *Earth and Planetary Science Letters*. 2021;562:116852. <https://doi.org/10.1016/j.epsl.2021.116852>.
- 26) Ma X, Gennaro MD, Giantomassi M, Verstraete MJ, Xu B. Ab initio calculation of thermoelectric properties in 3d ferromagnets based on spin-dependent electron–phonon coupling. *New Journal of Physics*. 2023;25(4):043022. <https://doi.org/10.1088/1367-2630/accca1>.
- 27) Hsieh W, Chiang Y, Deschamps F, Chen C, Chang J, Ikuta D, et al. Moderate Thermal Conductivity of Fe-Ni-Si Alloy at Earth's Core Conditions: Implications for Core Thermal Evolution and Geodynamo. *Geophysical Research Letters*. 2025;52:e2025GL117576. <https://doi.org/10.1029/2025GL117576>.
- 28) Tröger JA, Hartmann S. Identification of the thermal conductivity tensor for transversely isotropic materials. *GAMM-Mitteilungen*. 2022;45(3–4):e202200013. <https://doi.org/10.1002/gamm.202200013>.
- 29) Jaoul O, Campbell IA, Fert A. Spontaneous resistivity anisotropy in Ni alloys. *Journal of Magnetism and Magnetic Materials*. 1977;5(1):23–34. [https://doi.org/10.1016/0304-8853\(77\)90193-7](https://doi.org/10.1016/0304-8853(77)90193-7).
- 30) Fert A, Campbell IA. Two-Current Conduction in Nickel. *Physical Review Letters*. 1968;21(16):1190–1192. <https://doi.org/10.1103/PhysRevLett.21.1190>.