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Numerical Simulation Study on Temperature Field Optimization of a Vertical Transverse Magnetic Field Heat Treatment Furnace

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Abstract

With the escalating functional requirements of electronic systems in new energy vehicles, the performance specifications for electronic components have become increasingly stringent. Nanocrystalline soft magnetic alloy cores processed via transverse magnetic field heat treatment exhibit exceptional electromagnetic properties, rendering them ideal candidates for electromagnetic interference (EMI) suppression components. However, conventional transverse magnetic field heat treatment furnaces suffer from severe temperature inhomogeneity, which degrades the soft magnetic performance of the cores. In this work, a three-dimensional numerical model of a vertical transverse magnetic field heat treatment furnace is established using SolidWorks 2022, and the temperature distribution is simulated and analyzed using Ansys Workbench 2022 R1. Structural optimizations are then implemented based on simulation results. To validate the simulation model, thermocouples are arranged at multiple points inside the furnace for real-time temperature monitoring, and the measured data are compared with simulation results. Numerical results demonstrate that increasing the number of deflectors of the circulating cooling fan from 8 to 12 reduces the temperature difference within the core working region from 14 °C to 11.08 °C. Further optimization of the heating resistance wire winding configuration — replacing irregular winding with uniform spiral winding at a pitch of 2 mm — lowers the furnace internal temperature difference to 7.59 °C. Experimental validation using the optimized furnace confirms a substantial improvement in inductance performance, with values increasing by 40%–45% compared with the original furnace. Transmission electron microscopy (TEM) characterization reveals that the average grain sizes of magnetic cores sampled from different furnace positions after optimization are all approximately 18–19 nm, with nearly overlapping grain size distribution curves, confirming the homogenization of the microstructure. Both simulation and experimental results demonstrate that improving furnace temperature uniformity facilitates the formation of uniformly sized nanocrystalline grains, thereby effectively enhancing the inductance performance of the cores. This work provides a reliable engineering solution for achieving stable performance in the mass production of high-performance nanocrystalline cores.

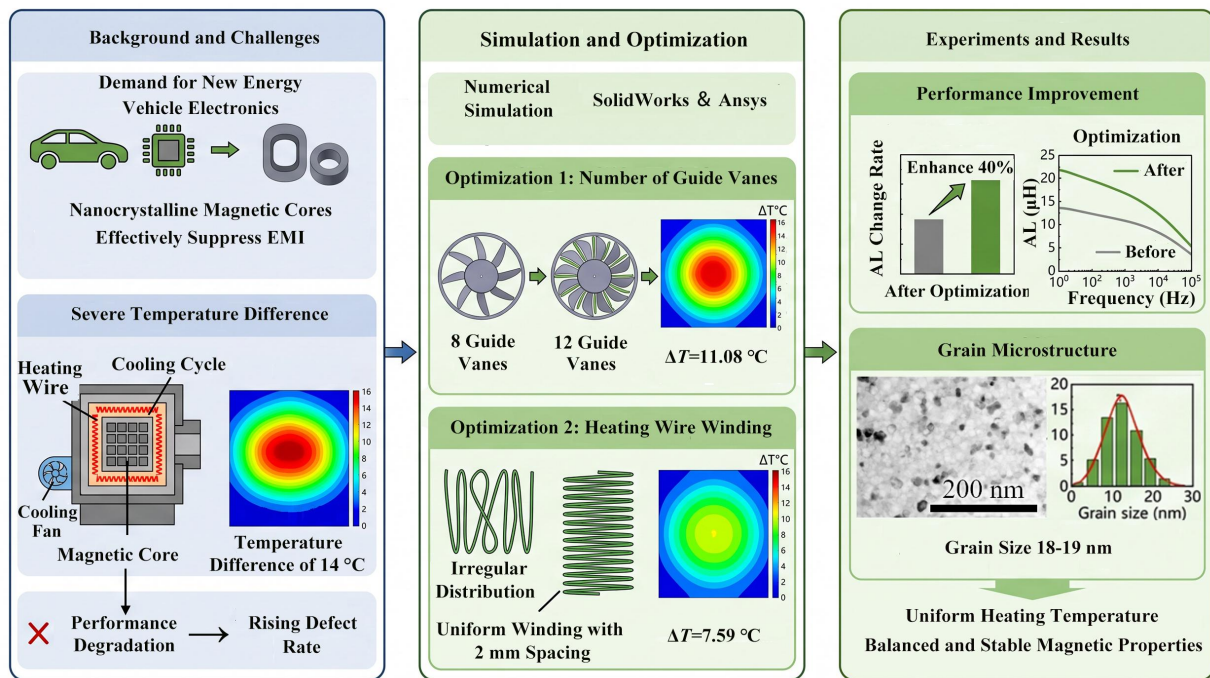
Keywords

Vertical transverse magnetic field heat treatment furnace; Temperature field; Deflector; Resistance wire with spiral pitch; Inductance performance

Citation: Mingshan Pan, Shaokang Wu, Chengzhi Jiang, *et al.* Numerical Simulation Study on Temperature Field Optimization of a Vertical Transverse Magnetic Field Heat Treatment Furnace. *Journal of High Performance Alloys and Processing*. 2026, 01 (1): 1-13. doi: [10.66729/jhpap202606039](https://doi.org/10.66729/jhpap202606039).



Graphic Abstract



Highlights

- A three-dimensional (3D) model of a vertical transverse magnetic-field heat-treatment furnace is built to identify the in-furnace temperature non-uniformity.
- Structural optimizations, including increased flow baffles and 2 mm equally-spaced spiral heating wires, decrease the furnace temperature difference from 14 °C to 7.59 °C according to simulation results.
- Thermocouple tests verify that structural optimization reduces furnace temperature difference to 8.50 °C, achieving a 40%–45% inductance improvement for heat-treated nanocrystalline cores.
- Transmission electron microscopy (TEM) observations confirm that uniform nanocrystalline microstructures are formed in magnetic cores at the top, middle, and bottom of the optimized furnace, with an average grain size of 18–19 nm.

1. Introduction

In the field of new energy vehicles, highly integrated electronic components inevitably generate electromagnetic interference (EMI) during operation, which can induce abnormalities in the control system and thereby pose a critical threat to vehicle safety^[1]. Nanocrystalline common-mode choke cores serve as pivotal components for EMI suppression, effectively attenuating EMI signals originating from electronic circuits. Their EMI suppression capability is closely correlated with high-frequency inductance performance, which can be significantly enhanced by transverse magnetic field heat treatment, enabling more effective EMI mitigation^[2]. During transverse magnetic field heat treatment, an external magnetic field perpendicular to the core length is applied, inducing ordered alignment of magnetic domains along a preferred orientation. This reduces domain wall pinning, enhances permeability, and substantially suppresses high-frequency losses^[3].

Temperature uniformity inside the furnace is a decisive indicator of core performance and manufacturing quality for vertical transverse magnetic field heat treatment furnaces. Precise regulation of temperature field parameters directly governs the nanocrystallization process. Temperatures below the critical crystallization temperature lead to insufficient precipitation of the nanocrystalline phase, degrading

magnetic properties. Conversely, temperatures exceeding the critical value induce excessive grain growth and secondary phase precipitation, impairing the microstructure and electromagnetic performance of nanocrystalline materials^[4].

Jaluria^[5] developed a two-dimensional steady-state temperature field model for a generic box-type heat treatment furnace using the finite difference method. Focusing on steady-state heat transfer, this study quantitatively analyzed the effects of heating element spacing and arrangement density on internal temperature gradients via numerical simulation. However, the model incorporated numerous idealized assumptions regarding structural parameters and boundary conditions, limiting its ability to accurately reproduce transient behavior and multiphysics coupling effects in practical production—a key bottleneck for subsequent research.

Mirzaei *et al.*^[6] identified critical structural limitations in conventional transverse magnetic field heat treatment furnaces based on industrial challenges. Unidirectional axial arrangement of heating elements, coupled with neglect of magnetic coil shielding effects on internal heat flow, results in pronounced temperature gradients, with typical temperature deviations exceeding 15 °C. Such deviations induce 8%–12% inconsistency in inductance values for batch-processed cores, severely compromising production yield. Their temperature field simulations confirmed the dominant role of temperature uniformity in determining the electromagnetic

performance of nanocrystalline cores.

Gao *et al.*^[2] investigated a pulse combustion heat treatment furnace, constructing a three-dimensional transient temperature field model with full coupling of radiation, conduction, and convection. Computational fluid dynamics (CFD) was employed to simulate turbulent gas flow within the furnace, incorporating thermophysical properties of lining materials. Installation of arc-shaped deflectors at the furnace midsection facilitated homogeneous hot gas distribution, reducing the temperature difference in the uniform temperature zone from 15 °C to 5 °C and increasing the length ratio of the uniform zone to total furnace length from 40% to 65%. This provides an industrially viable technical framework for temperature field optimization of vertical transverse magnetic field heat treatment furnaces.

This study addresses the critical issue of temperature inhomogeneity during heat treatment in a vertical transverse magnetic field heat treatment furnace. A three-dimensional geometric model is established using SolidWorks 2022 (SolidWorks 2022; Dassault Systèmes SolidWorks Corporation: Waltham, Massachusetts, USA), and the temperature field distribution is numerically simulated using Ansys Workbench 2022 R1 (Ansys Workbench 2022 R1; ANSYS, Inc.: Canonsburg, Pennsylvania, USA) finite element software. Structural optimizations are then

performed based on the simulation results. For temperature measurement, thermocouples are arranged at multiple points for real-time monitoring, and the measured data are compared with the simulation results. Finally, magnetic cores are fabricated using the optimized furnace. The inductance performance of the amorphous nanocrystalline cores is characterized using an Inductance-Capacitance-Resistance (LCR) digital bridge, and the microstructure of the cores is observed by transmission electron microscopy (TEM) to analyze grain size distribution, thereby verifying the optimization effectiveness at the microstructural level. All experimental data are plotted and analyzed using OriginPro 2021 (OriginPro 2021; OriginLab Corporation: Northampton, Massachusetts, USA).

2. Model Establishment

This study focuses on a vertical transverse magnetic field heat treatment furnace utilized in industrial production at Guangdong Zhongfu New Material Technology Co., Ltd. A three-dimensional solid model is constructed using SolidWorks software, adhering to the actual dimensions and material properties of the equipment. Key technical parameters are summarized in **Table 1**.

Table 1. Technical parameters of the vertical transverse magnetic field heat treatment furnace

Component	Dimension Parameters	Material
Frame	1,600 × 1,650 mm	A3
Furnace Liner	360 × 1,200 mm	SUS304
Heating Resistance Wire	$\Phi = 2$ mm	Cr ₂₀ Ni ₈₀ alloy
Insulation Cotton	20 mm	Aluminum silicate fiber
Magnetizing Coil	4 × 15 mm	Flat aluminum strip
Circulating Cooling Fan	$\Phi = 200$ mm	SUS321

The furnace structure is schematically illustrated in **Figure 1**, comprising three primary subsystems: the heating module, magnetizing module, and furnace body. The heating module consists

of carbon-ceramic heating wires, insulation cotton, and a cooling fan. The magnetizing module incorporates a magnetizing coil. The furnace body includes the liner, furnace cover, and circulating cooling fan.

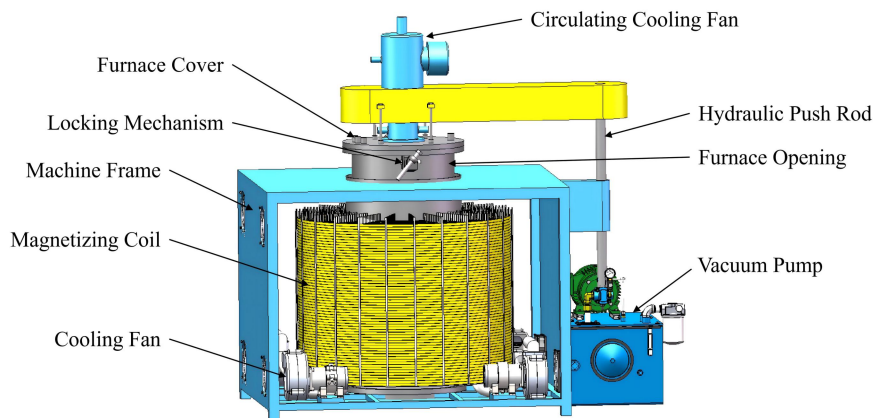


Figure 1. Structural diagram of the vertical transverse magnetic field heat treatment furnace. Copyright: Drawn with SolidWorks 2022.

3. Simulation and Analysis of the Vertical Transverse Magnetic Field Heat Treatment Furnace

3.1 Heat Transfer Analysis

As illustrated in **Figure 2**, heat transfer within the vertical transverse magnetic field heat treatment furnace is predominantly governed by thermal radiation^[8], with thermal convection^[2] and

thermal conduction^[10] acting as secondary mechanisms. During operation, Joule heat generated by the heating resistance wire is radiated to the furnace wall and subsequently re-radiated from the inner surface of the furnace liner to the core surfaces. High-purity argon serves as the protective atmosphere; buoyancy-driven ascent of hot argon and descent of cold argon establish natural convection, while the circulating cooling fan enhances argon

circulation to accelerate heat distribution. Multi-layer stacked cores undergo conductive heat transfer from the surface to the interior. Owing to the low thermal conductivity of nanocrystalline cores, adequate holding time and precise annealing temperature

are essential for homogeneous microstructural evolution^[11]. A mathematical model is therefore developed based on Fourier's heat conduction differential equation to characterize the temperature field distribution^[12].

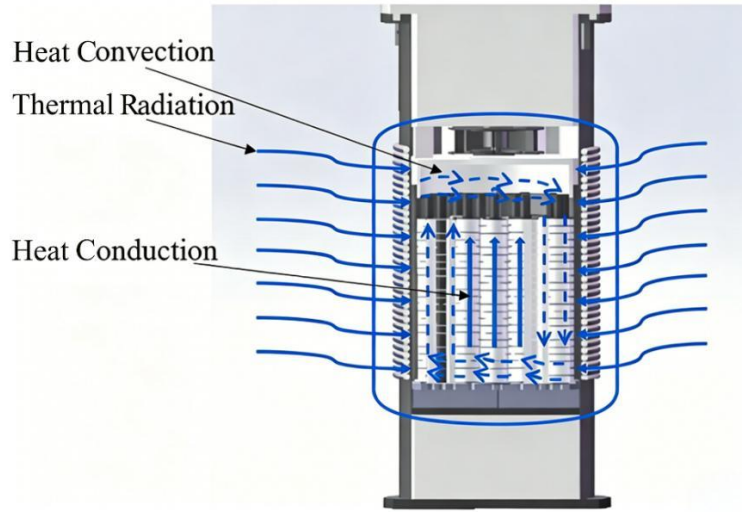


Figure 2. Heat transfer diagram of the vertical transverse magnetic field heat treatment furnace. Copyright: Drawn with Microsoft PowerPoint 2021.

In the temperature field simulation, Joule heat released by the heating resistance wire serves as the primary heat source^[13]. Upon current conduction through the resistance wire, the volumetric heat generation is defined by Joule's law:

$$q_v = \frac{I^2 R}{V} \quad (2-1)$$

where I is the current (A), R is the resistance of the wire (Ω), and V is the volume of the wire (m^3); q_v is the internal heat source, in kJ.

The furnace liner is cylindrical, and heat transfer therein is modeled as a three-dimensional transient heat conduction problem in cylindrical coordinates. The temperature evolution is governed by Fourier's heat conduction differential equation:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{1}{r^2} \frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2} + \frac{q_v}{k} = \frac{\rho c}{k} \frac{\partial T}{\partial t} \quad (2-2)$$

r is the radius in cylindrical coordinates, k is the thermal conductivity, and T is the temperature. Although equation (2-2) presents the general form of transient heat conduction, the simulation objective of this study is the temperature distribution inside the furnace after long-term operation to reach thermal equilibrium, i.e., a temperature field independent of time. Accordingly, the time derivative term is set to zero in the steady-state thermal analysis module of Ansys Workbench 2022 R1, and the steady-state solver is adopted for computation. This treatment is consistent with the practical production condition where the furnace is held at a constant temperature for an extended period with temperature fluctuations less than ± 1 °C. All subsequent simulation results correspond to steady-state temperature fields.

Thermal radiation refers to a heat exchange process in which an object emits electromagnetic energy that is subsequently absorbed and converted into thermal energy, accompanied by mutual conversion between thermal energy and radiant energy^[14]. The higher the temperature of an object, the greater the amount of heat it radiates per unit time. Radiative heat transfer can occur in a vacuum with the highest efficiency^[15].

In practical radiative heat transfer, the radiative heat transfer rate of an object can be calculated according to the Stefan-Boltzmann law^[16], and the calculation formula is expressed as follows:

$$\phi = \varepsilon \sigma A T^4 \quad (2-3)$$

where ϕ is the radiative heat transfer rate (W), ε is the emissivity, σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W}/(\text{m}^2 \cdot \text{K}^4)$), A is the radiating area (m^2), and T is the thermodynamic temperature (K).

Equation (2-3) quantifies the radiative heat transfer rate of a surface. In radiative exchange between two surfaces, the view factor F_{ij} is defined as the fraction of radiation leaving surface i that impinges on surface j . This parameter depends on the geometry, dimensions, orientation, and separation of the surfaces, and can be determined via direct integration:

$$F_{ij} = \frac{1}{A_i} \iint \frac{\cos(\alpha_i) \cos(\alpha_j)}{\pi r^2} dA_j dA_i \quad (2-4)$$

where A_i and A_j are the radiating areas of surfaces i and j (m^2). The radiative heat transfer rate between two surfaces can be calculated using a modified form of the Stefan-Boltzmann law.

The radiative heat transfer between the heating resistance wire and the furnace wall in the transverse magnetic field heat treatment furnace is given by:

$$-k \frac{\partial T}{\partial r} = \varepsilon \sigma F_{ij} (T_i^4 - T_j^4) \quad (2-5)$$

k is the thermal conductivity, where F_{ij} is the view factor (the fraction of energy leaving surface i that reaches surface j , a number ≤ 1), and T_i and T_j are the surface temperatures of objects i and j (K).

3.2 Thermophysical Parameters of the Furnace

This study primarily employs radiative heat transfer theory to analyze the temperature field within the furnace liner. For the temperature distribution simulation, the ambient temperature is set at 25 °C. The thermophysical properties of the key components are summarized in Table 2^[17-20].

Table 2. Thermophysical parameters of the vertical transverse magnetic field heat treatment furnace

Component	Material	Specific Heat/(kJ/kg·K)	Density/(g/cm ³)	Thermal Conductivity/(W/m·K)	Emissivity/ ϵ
Furnace Liner	SUS304	0.58	7.73	23.11	0.80
Heating Resistance Wire	Cr ₂₀ Ni ₈₀	0.46	8.40	15	0.80
Insulation Cotton	Aluminum silicate fiber	1.10	0.12	0.13	0.80

The magnetizing coil is fabricated from a flat aluminum strip (commercially pure aluminum), with thermophysical properties listed as follows: density of 2,705 kg/m³, specific heat capacity of 900 J/(kg·K), thermal conductivity of 230 W/(m·K), and electrical resistivity of $2.78 \times 10^{-8} \Omega \cdot \text{m}$. The Joule heat generated by the magnetizing coil is not incorporated as a heat source in the temperature field simulation for the following reasons. First, a DC excitation current is applied to the coil to generate a constant transverse magnetic field, and heating is not its primary function. Second, the Joule heating power of the coil is far lower than that of the heating resistance wire, accounting for less than 2% of the

heating wire power. Third, the coil is arranged outside the furnace lining; the heat it generates is mainly dissipated outward through the furnace wall, and its influence on the temperature distribution inside the furnace chamber can be neglected.

3.3 Mesh Generation for Temperature Field Simulation

The temperature field simulation adopts adaptive meshing in Ansys Workbench to discretize the furnace model. The simulated nanocrystalline amorphous core measures 80 mm $\times$ 50 mm $\times$ 20 mm. A uniform element size of 1 mm is specified, yielding 441,743 nodes and 139,295 elements. The resulting mesh is presented in **Figure 3**.



Figure 3. Mesh of the transverse magnetic field heat treatment furnace. Copyright: Drawn with Ansys Workbench 2022 R1.

To ensure that the simulation results are independent of mesh size, two sets of meshes with different densities were adopted for mesh independence verification in this study: a coarse mesh (element size of 2 mm with approximately 32,000 elements) and a fine mesh (element size of 0.50 mm with approximately 556,000 elements). Under identical boundary conditions and heat source parameters, temperatures at five characteristic points selected along the axial direction within the core heating zone were calculated separately. The results reveal that the maximum temperature deviation between the coarse mesh and the adopted mesh is 2.30 °C, while the maximum deviation between the fine mesh and the adopted mesh is only 0.60 °C. In addition, the variation range of the maximum temperature difference in the heating zone among the three mesh schemes is less than 1 °C. Taking both computational efficiency and accuracy into consideration, a mesh size of 1 mm was selected, which meets the requirements of engineering simulation. All subsequent analyses are performed based on this mesh.

3.4 Boundary Condition Settings

Based on the furnace's heat transfer characteristics and practical operating conditions, the ambient temperature is set to 25 °C. The initial condition is defined as $T = T_0$ at $t = 0$. The boundary conditions are specified as follows: (1) The heating resistance wire serves as the primary heat source, with its volumetric heat generation rate applied as a thermal load. (2) Thermal radiation dominates internal heat transfer, with an emissivity of $\epsilon = 0.80$. (3) The

furnace wall is treated as a stationary no-slip boundary. (4) High-purity argon is introduced as a protective atmosphere to prevent core oxidation during operation.

Thermophysical properties of the nanocrystalline magnetic core serve as critical input parameters for temperature field simulations. The magnetic core adopted in this work is a toroidal core wound from 1K107B Fe-based nanocrystalline ribbons. Its density is taken as 7.20 g/cm³ according to the manufacturer's specification. The specific heat capacity is set to 0.48 kJ/(kg·K) with reference to data of similar Fe₇₈B₁₃Si₉ nanocrystalline alloys and pure iron. Previous investigations have demonstrated that the thermal conductivity k of Finemet-type amorphous and nanocrystalline alloys ranges approximately from 5 to 15 W/(m·K), and remains nearly constant once the annealing temperature exceeds 500 °C^[21]. Assuming that the thermal conductivity of the amorphous nanocrystalline magnetic core is temperature-independent within the annealing temperature window, $k = 10 \text{ W/(m·K)}$ is adopted in the present study on the basis that Ma *et al.*^[22] measured a thermal conductivity of 10.38 W/(m·K) for Finemet-type alloys.

The natural convection heat transfer coefficient between the outer furnace wall and ambient air is empirically set to 8 W/(m²·K). This value is estimated using the correlation for natural convection over vertical plates under the condition of a wall temperature of roughly 100 °C and an ambient temperature of 25 °C. High-purity argon (99.999%) is used as the protective gas. At an average furnace temperature of approximately 550 °C, its thermophysical

parameters are as follows: density $\approx 0.60 \text{ kg/m}^3$, specific heat capacity $\approx 0.52 \text{ kJ/(kg}\cdot\text{K)}$, thermal conductivity $\approx 0.058 \text{ W/(m}\cdot\text{K)}$, and dynamic viscosity $\approx 4.20 \times 10^{-5} \text{ Pa}\cdot\text{s}$. The circulating cooling fan operates at a rotational speed of 2,800 rpm with an impeller diameter of 200 mm. Accordingly, the gas velocity at the fan outlet is estimated to be about 12 m/s. The corresponding Reynolds number, using the furnace inner diameter of 360 mm as the characteristic length, is approximately 2.20×10^4 , indicating a turbulent flow regime of the protective gas inside the furnace, which facilitates uniform heat distribution. All the above parameters are implemented in the simulation setup to guarantee the reproducibility of results.

3.5 Temperature Field Simulation Before Structural Optimization

To accurately investigate the temporal evolution of temperature inside the transverse magnetic field heat treatment furnace, thermocouples were employed as temperature sensors in accordance with the practical configuration of the company's self-developed heat treatment furnace. Fixed-point temperature tracking on the magnetic cores inside the furnace was carried out

prior to calculations to fully characterize the internal temperature distribution. The interior of the transverse magnetic furnace is generally cylindrical. Therefore, temperature monitoring points were uniformly arranged along the vertical direction from the top to the bottom of the magnetic cores. A total of six monitoring points, denoted as P1, P2, P3, P4, P5 and P6 were set up to comprehensively describe the distribution and uniformity of the temperature field within the furnace.

The measured temperature data before optimization are listed in **Table 3**. Restricted by its structural design, the vertical transverse magnetic heat treatment furnace exhibits inherent temperature non-uniformity, with a temperature difference of approximately 15 °C within the core working zone. Under practical production conditions, after the toroidal magnetic cores are heat-treated in the unoptimized furnace, the inductance values at the top and bottom regions are relatively low. By contrast, the inductance performance of the cores in the middle layer shows a relatively uniform distribution, yet the magnitude of inductance fails to reach the target level.

Table 3. Measured temperature data inside the furnace before optimization

Monitoring Point	Position Description	Measured Temperature / °C
P1	Top (position of the uppermost magnetic core)	552.20
P2	Upper-middle region	547.50
P3	Upper-central region	544.80
P4	Lower-central region	542.60
P5	Lower-middle region	541.30
P6	Bottom (position of the lowermost magnetic core)	537.30

Figure 4 presents the simulated temperature nephogram of the furnace chamber before structural optimization. The results reveal that the temperature difference within the magnetic core heating zone reaches 14 °C, with temperatures ranging from a maximum of approximately 550 °C at the top to a minimum of roughly 536 °C at the bottom. The temperature field exhibits a distinct spatial gradient: the top region has the highest temperature of up to 550 °C, the middle

region features a relatively uniform temperature distribution, and the bottom region shows the lowest temperature at about 536 °C. Temperature gradually decreases vertically from the top to the bottom, and this distribution pattern is consistent with observations from actual production. Such temperature inhomogeneity causes the inductance of nanocrystalline magnetic cores to vary with position, lowering the product qualification rate and increasing manufacturing costs.

Unoptimized Structure
Type: Temperature
Unit: °C
Time: 1
Max: 550.23
Min: 536.26

550.23
549.59
548.17
546.75
545.23
543.91
542.49
540.07
538.65
536.23

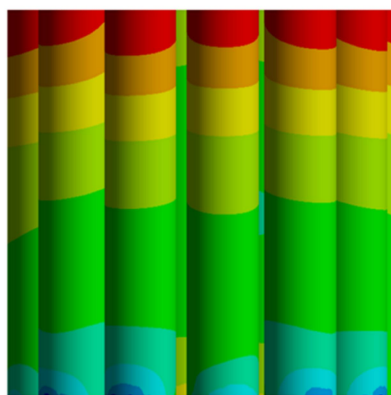


Figure 4. Temperature field simulation cloud map before structural optimization. Copyright: Drawn with Ansys Workbench 2022 R1.

4. Structural Optimization Analysis and Validation

4.1 Optimization of Circulating Cooling Fan Deflectors

The circulating cooling fan employs deflectors to drive the protective gas flow inside the furnace, disrupting natural-convection-induced thermal stratification and improving temperature uniformity. However, the original deflector design is

simplicistic, featuring a small number of irregularly arranged vanes. This leads to inefficient hot-gas circulation, local heat accumulation, pronounced temperature gradients, and a large overall temperature difference. To mitigate such inhomogeneity, the number of fan-mounted deflectors is optimized. As illustrated in **Figure 5**, the count is increased from 8 to 12, with a uniform circumferential distribution around the fan.

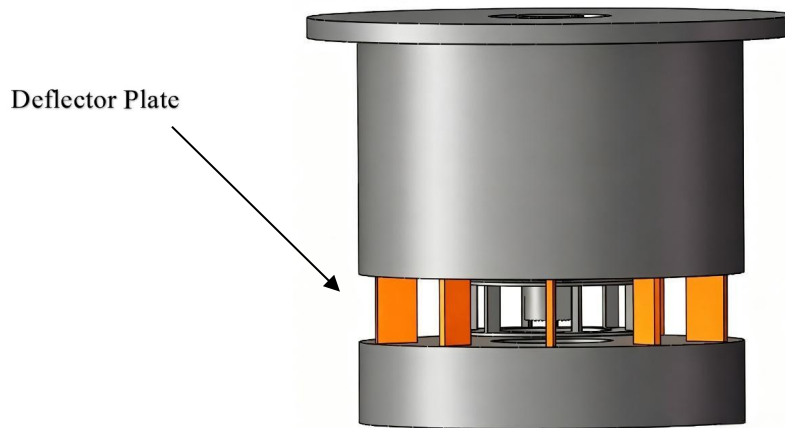


Figure 5. Optimized deflector structure. Copyright: Drawn with SolidWorks 2022.

Figure 6 shows the temperature field simulation performed with identical heat treatment process parameters. The results indicate that the temperature difference in the effective heating zone for magnetic cores decreased from 14 °C before optimization to 11.08 °C, with a maximum temperature of approximately 548 °C at the top and a minimum temperature of around 537 °C at

the bottom. The temperature distribution in the middle region is relatively uniform. The temperature gradually declines from the top to the bottom, maintaining a consistent vertical temperature gradient. Twelve flow deflectors guide the hot gas inside the furnace to form a stable upward spiral flow, improving circulation efficiency and consequently enhancing temperature uniformity.

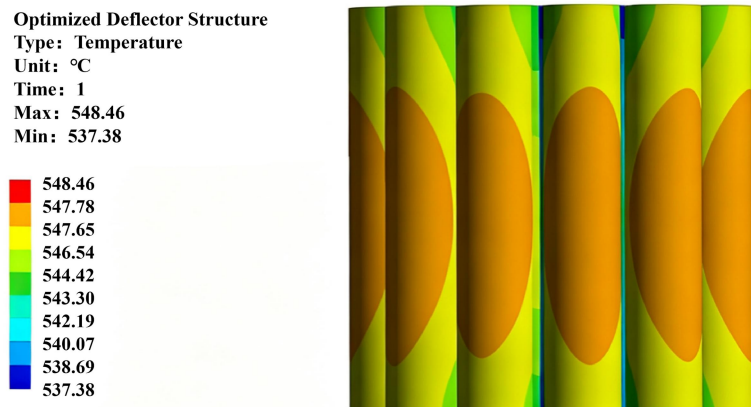


Figure 6. Temperature field simulation cloud map after deflector optimization. Copyright: Drawn with Ansys Workbench 2022 R1.

To validate the practical effect of the deflector optimization, 80 mm × 50 mm × 20 mm cores fabricated in the optimized furnace are characterized via an LCR digital bridge, and their

inductance values are compared with those obtained from the unoptimized configuration. The results are presented in **Figure 7**.

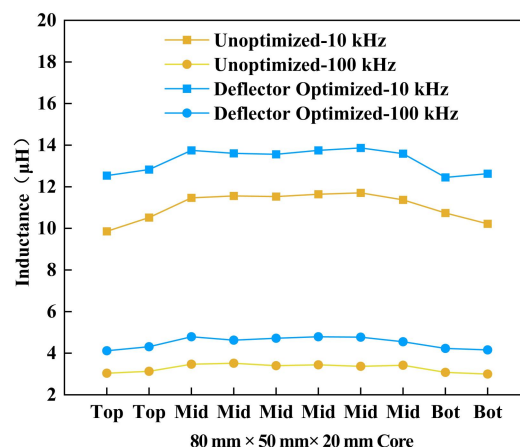


Figure 7. Comparison of inductance values of 80 mm × 50 mm × 20 mm cores before and after deflector optimization. Copyright: Drawn with OriginPro 2021.

As clearly shown in **Figure 7**, deflector optimization significantly improves the inductance of 80 mm × 50 mm × 20 mm cores at both 10 kHz and 100 kHz. Inductance increases across all furnace positions, with a moderate improvement in the middle zone and more pronounced enhancements at the top and bottom.

Before optimization, obvious discrepancies existed in the inductance of magnetic cores placed at different furnace positions. It can be seen from **Table 4** that the magnetic cores in the middle region

exhibit the highest Inductance Factor (A_L) (11.55 μH), the magnetic cores at the bottom show the lowest A_L (10.48 μH), and the magnetic cores at the top take an intermediate value (10.19 μH), with a maximum positional difference of 1.36 μH . This distribution trend is consistent with the characteristics of the temperature field prior to optimization. Excessively high temperature at the top induced grain coarsening, while insufficient temperature at the bottom led to inadequate crystallization; both factors degraded the inductive performance.

Table 4. Inductance values of 80 mm × 50 mm × 20 mm magnetic cores before and after baffle optimization

Position in Furnace	A_L Before Optimization (μH)	A_L After Flow Baffle Optimization (μH)	Improvement Rate (%)
Top	10.19 ± 0.47	12.69 ± 0.21	24.50
Mid	11.55 ± 0.12	13.69 ± 0.12	18.50
Bot	10.48 ± 0.37	12.54 ± 0.13	19.70

NOTE: Data are expressed as mean ± standard deviation; 10 samples were repeatedly tested at each position; Improvement rate = (Mean value after optimization – Mean value before optimization) / Mean value before optimization × 100%. A_L : Inductance Factor.

After the number of flow baffles was increased from 8 to 12, the inductance at all three positions improved remarkably. The bottom region achieved the largest enhancement rate (19.70%), followed by the top region (24.50%), whereas the middle region showed a relatively moderate improvement (18.50%). The inductance values at the top and bottom approached those of the middle zone, and the maximum difference among the three positions was reduced to 1.15 μH . The results indicate that improved circulation efficiency of hot gas effectively weakens the axial temperature gradient within the furnace chamber, enabling magnetic cores at various positions to undergo more uniform heat treatment.

These findings confirm that deflector optimization reduces the inter-zone temperature difference to approximately 11.08 °C, effectively enhancing thermal stability and uniformity during heat treatment and thereby substantially improving core inductance performance.

4.2 Optimization of Heating Resistance Wire Winding Pattern

Nanocrystalline cores are primarily heated via thermal radiation

from the resistance wire wrapped around the furnace liner. The original winding configuration exhibits inherent drawbacks, leading to excessive heat loss, temperature fluctuations, and inter-regional temperature disparities.

Following deflector optimization (Section 3.1), both simulation and experimental results confirm a notable reduction in the core-zone temperature difference. Accordingly, the heating resistance wire winding pattern is further optimized, and the synergistic effect of combined deflector and wire optimization is investigated.

As illustrated in **Figure 8**, guided by the spatial temperature distribution, the resistance wire is uniformly wound in a spiral layout with a 2 mm pitch. This arrangement homogenizes heating power distribution and improves internal temperature uniformity. Additionally, a supplementary insulation cotton layer is installed around the resistance wire to mitigate conductive heat loss through the liner wall, effectively reducing energy dissipation and enhancing thermal efficiency.



Figure 8. Model of a heating resistance wire with an optimized winding pattern. Copyright: Drawn with SolidWorks 2022.

Figure 9 presents the simulated temperature field results after optimizing the winding mode of resistance wires. The temperature difference in the magnetic core heating zone is further reduced to 7.59 °C, with a maximum temperature of approximately 550 °C at the top and a minimum temperature of roughly 542 °C at the bottom. The temperature in the middle

region stabilizes at around 546 °C. The overall temperature distribution becomes more concentrated, verifying a remarkable improvement in temperature uniformity. The optimized helical winding structure with a pitch of 2 mm delivers a more uniform distribution of heating power, effectively eliminating local hot spots and cold zones.

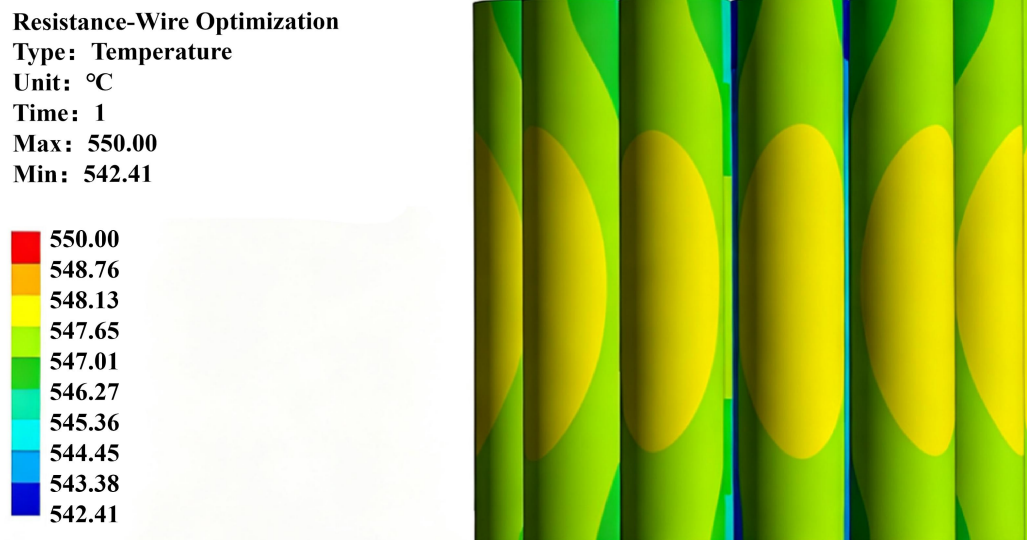


Figure 9. Temperature field simulation cloud map after heating resistance wire optimization. Copyright: Drawn with Ansys Workbench 2022 R1.

To verify the practical effect of the combined optimization scheme, thermocouple sensors were arranged in accordance with the layout of temperature measurement points adopted prior to optimization for real-time temperature monitoring inside the furnace. The measured temperatures were then compared with the simulation results.

It can be concluded from the data in **Table 5** and **Table 6** that slight deviations exist between the measured and simulated values, whereas such deviations are within the acceptable range for engineering applications. The discrepancies may arise from the fact that the temperatures extracted from simulation contours correspond to nodal temperatures in the furnace cavity, while the measured data

represent surface temperatures of magnetic cores, indicating a difference in physical locations. In addition, several factors contribute to the deviations, including the large thermal capacity and strong thermal inertia of stacked magnetic cores in the practical furnace, as well as local turbulence effects of the protective gas flow. Nevertheless, the simulated and measured results exhibit consistent variation trends of temperature difference. This demonstrates that the combined optimization scheme effectively improves the temperature uniformity inside the furnace, and the established simulation model can reliably predict the optimization trend of the internal temperature field.

Table 5. Measured temperatures at monitoring points after combined optimization

Monitoring Point	Position Description	Measured Temperature / °C
P1	Top (position of the uppermost magnetic core)	551.10
P2	Upper-middle region	548.80
P3	Upper-central region	547.60
P4	Lower-central region	546.20
P5	Lower-middle region	545.30
P6	Bottom (position of the lowermost magnetic core)	542.60

Table 6. Simulated versus measured temperature differences after combined optimization

Comparative Working Conditions	Simulated Temperature Difference / °C	Measured Temperature Difference / °C	Absolute Error	Relative Error (%)
Before Optimization	14	15	1	6.70
After Combined Optimization	7.59	8.50	0.91	10.70

To validate the practical efficacy of the combined optimization (deflectors plus resistance wire), 80 mm × 50 mm × 20 mm cores are fabricated in the doubly optimized furnace. Their inductance

values are compared with those obtained under deflector-only optimization (Section 3.1). The measurement results are illustrated in **Figure 10**.

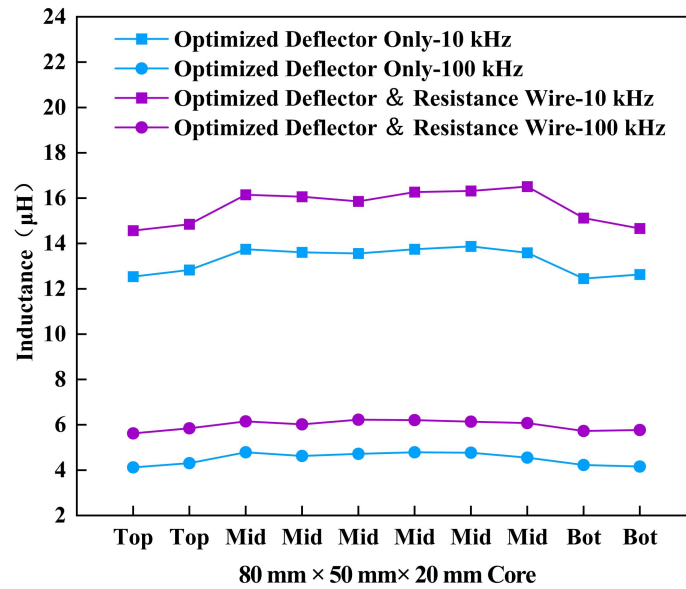


Figure 10. Comparison between the optimized deflector and the optimized deflector & resistance wire. Copyright: Drawn with OriginPro 2021.

Further enhanced thermal stability and uniformity are achieved via resistance wire layout optimization. As depicted in **Figure 10**, the inductance of 80 mm × 50 mm × 20 mm cores rises further under various test frequencies. The joint optimization of deflector quantity and resistance wire winding configuration effectively promotes core inductance characteristics.

On the basis of flow baffle optimization, further enhancement

in inductance is achieved after the heating wires are rearranged from irregular winding to spiral winding with an equal spacing of 2 mm. As shown in **Table 7**, the further improvement rates at the top, middle and bottom positions are 15.90%, 18.30% and 18.70%, respectively. The maximum inductance difference among the three positions is further reduced to 1.31 μH, and the inductance range after comprehensive optimization is from 14.71 μH to 16.20 μH.

Table 7. Inductance comparison of 80 mm × 50 mm × 20 mm magnetic cores after flow baffle optimization and combined optimization

Position in Furnace	A_L after Flow Baffle Optimization (μH)	A_L after Combined Optimization (μH)	Further Improvement Rate (%)
Top	12.69 ± 0.21	14.71 ± 0.20	15.90
Mid	13.69 ± 0.12	16.20 ± 0.22	18.30
Bot	12.54 ± 0.13	14.89 ± 0.33	18.70

NOTE: Further improvement rate = (Post-combined-optimization mean – Post-baffle-optimization mean) / Post-baffle-optimization mean × 100%.

At a test frequency of 100 kHz, the variation trend of inductance is consistent with that at 10 kHz. Before optimization, the average inductance values at the top, middle and bottom are 3.09 ± 0.06 μH, 3.44 ± 0.05 μH, and 3.04 ± 0.06 μH, respectively. After flow baffle optimization, these values increase to 4.22 ± 0.13 μH, 4.71 ± 0.10 μH, and 4.20 ± 0.05 μH. Following combined optimization, the inductances are further raised to 5.74 ± 0.16 μH, 6.14 ± 0.08 μH, and 5.75 ± 0.03 μH. The inductance at each position exhibits a consistent monotonic increasing trend at different frequencies, which verifies the stability and effectiveness of the proposed optimization scheme.

Temperature discrepancy at diverse positions triggers inconsistent crystallization behaviors and distinct magnetic properties. Cores exposed to excessive temperature suffer abnormal grain growth and secondary phase separation, which degrade soft magnetic performance. Insufficient temperature leads to inadequate precipitation of nanocrystalline phases and low inductance. A satisfactory fine and homogeneous nanocrystalline microstructure with superior magnetic properties can only form within the optimal temperature range. Non-uniform thermal distribution causes uneven crystallization degree, resulting in prominent inductance fluctuation among batch products and declined production yield. Accordingly,

structural optimization that homogenizes internal furnace temperature enables consistent crystallization temperature for all cores, which is essential to obtain steady outstanding soft magnetic performance and enhance batch production consistency.

4.3 Microstructural Characterization and Grain Size Analysis

To reveal the intrinsic mechanism for the improvement of magnetic core inductance performance induced by temperature uniformity optimization from a microscopic perspective, samples were cut from three typical positions (top, middle, and bottom) inside the furnace from 80 mm × 50 mm × 20 mm magnetic cores heat-treated in the furnace after combined optimization. TEM observation and statistical analysis of grain size were subsequently carried out.

Figure 11 shows bright-field TEM micrographs of magnetic cores treated in the furnace after combined optimization. The grains at the top, middle and bottom positions exhibit fine, uniform and equiaxed nanocrystalline morphology, and no abnormally grown grains are observed. This indicates that the reduced temperature difference inside the furnace after optimization facilitates the nucleation and growth of nanocrystals throughout the effective heating zone, ensuring synchronous and consistent crystallization behavior of magnetic cores at various positions.

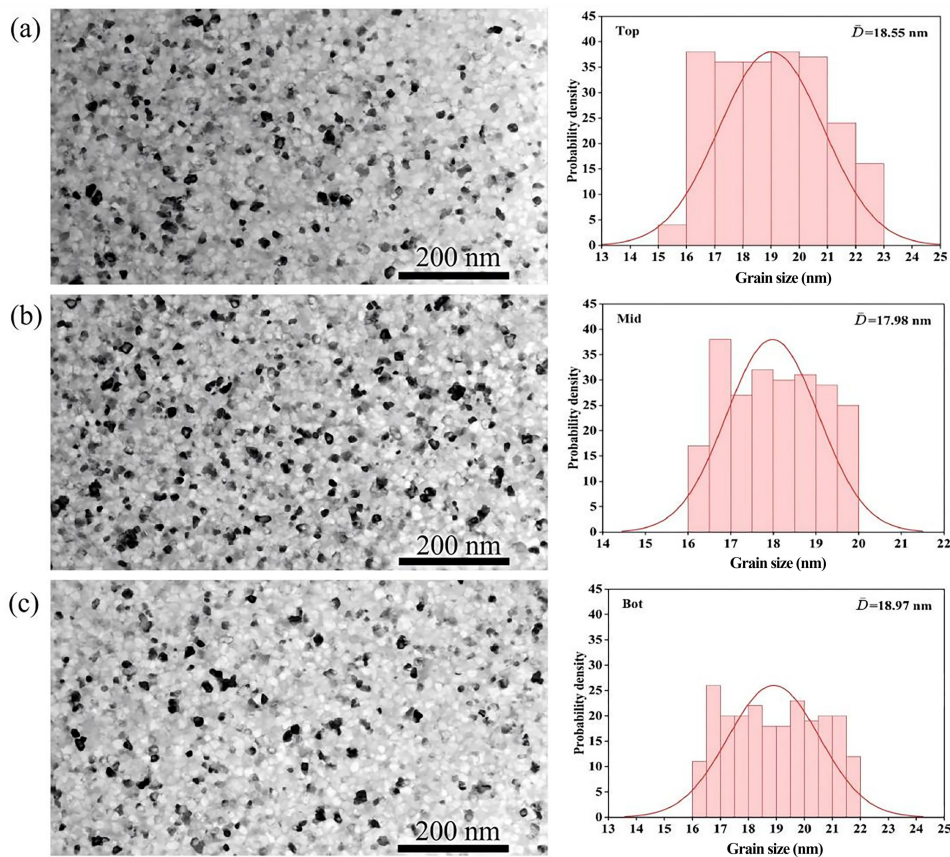


Figure 11. Bright-field transmission electron microscopy (TEM) micrographs and corresponding grain size probability density distribution curves of nanocrystalline cores sampled from different positions inside the furnace after combined optimization. (a) Top; (b) Middle; (c) Bottom. Scale bar: 200 nm. **NOTE:** $\bar{D}$: the standard symbol for the average grain size. Copyright: Drawn with PowerPoint.

The grain size probability density distribution curves corresponding to the TEM micrographs of samples from the three positions display ideal unimodal Gaussian distributions. The grain sizes are mainly distributed in the range of 14–23 nm, with all peaks centered at approximately 18 nm. The average grain sizes of the three groups are 18.55 ± 2.09 nm for the top, 17.98 ± 1.96 nm for the middle, and 18.97 ± 2.14 nm for the bottom, and the maximum difference in average grain size is only 0.99 nm. The statistical results are in good agreement with TEM observations. The grain sizes of magnetic cores at different furnace positions become highly consistent after optimization, further verifying the positive effect of improved temperature uniformity on microstructure.

Combining TEM morphological observations and grain size statistical analysis, the combined structural optimization improves furnace temperature uniformity, which effectively suppresses grain coarsening and insufficient crystallization induced by axial temperature gradients. Consequently, fine and homogeneous nanocrystalline microstructures are obtained in magnetic cores at all positions.

4.4 Analysis of Contribution Proportion and Coupling Effect of Two Optimization Mechanisms

The two optimization strategies exhibit essential differences in the improvement mechanism of furnace temperature uniformity. The flow baffle optimization improves the circulation of protective gas inside the furnace and enhances the convective heat transfer efficiency by increasing the number of baffles. It breaks the thermal stratification caused by natural convection, thereby

indirectly homogenizing the temperature distribution on the inner wall of the furnace lining. In contrast, the heating wire winding optimization rearranges the irregularly wound heating wires into a spiral structure with a uniform spacing of 2 mm. This method directly adjusts the axial distribution of heating power, achieves uniform heat flux input on the furnace wall per unit length, and fundamentally inhibits local overheating and undercooling phenomena.

According to the step-by-step differential analysis of simulation results, the single application of flow baffle optimization reduces the maximum furnace temperature difference from 14 °C to 11.08 °C, representing a temperature drop of 2.92 °C and accounting for 45.50% of the total temperature reduction of 6.41 °C. On this basis, the additional heating wire winding optimization further decreases the temperature difference to 7.59 °C, with an extra temperature reduction of 3.49 °C, contributing the remaining 54.50% of the total improvement. The two optimization measures show comparable contribution ratios and present a favorable superposition and enhancement effect.

The physical origin of this synergistic effect is clarified as follows. Flow baffle optimization improves the macroscopic temperature uniformity of the furnace chamber but cannot eliminate local thermal zones induced by the uneven layout of heating wires. Heating wire optimization corrects this inherent defect from the perspective of heat source distribution. If only flow baffle optimization is adopted, the furnace temperature difference remains at 11.08 °C. Although the inductance consistency of magnetic cores is improved, the overall performance still has obvious deficiencies.

By contrast, if only the heating wire winding is optimized without improving gas flow circulation, the heat released by the uniform heat source will still accumulate locally due to gas flow short-circuiting and flow stagnation. The coupling effect of the two measures demonstrates an approximately linear superposition characteristic under the working conditions in this study.

5. Conclusion

(1) Based on Fourier's heat conduction differential equation, Joule's law, and the Stefan-Boltzmann radiation law, a three-dimensional transient heat transfer mathematical model is established for the vertical transverse magnetic field heat treatment furnace. Joule heat generated by the heating resistance wire is determined as the dominant heat source. The coupled heat transfer mechanisms of thermal radiation, thermal convection, and thermal conduction inside the furnace are elucidated, which provides a reliable theoretical basis for the temperature field simulation and structural optimization of the furnace.

(2) The proposed two structural optimization strategies effectively mitigate the internal temperature difference of the furnace. Increasing the number of deflectors for the circulating cooling fan from 8 to 12 optimizes the internal hot gas circulation efficiency, reducing the temperature difference in the core heating zone from 14 °C to 11.08 °C. Furthermore, replacing the irregular layout of the heating resistance wire with a uniform spiral winding structure at a 2 mm pitch further lowers the maximum temperature difference to 7.59 °C, which significantly enhances the overall internal temperature uniformity of the furnace.

(3) The two structural optimizations significantly enhance the inductance performance of nanocrystalline cores. After deflector optimization, the inductance of 80 mm × 50 mm × 20 mm cores at different furnace positions increases by approximately 18% to 25%. With the subsequent heating wire optimization, the inductance further improves by about 16% to 19%, yielding a total enhancement of 40% to 45% compared with the original furnace, with well-balanced improvements across all positions. TEM characterization reveals that the average grain sizes of cores at different furnace positions after optimization are all approximately 18 nm to 19 nm, and the grain size distribution curves nearly overlap, confirming the homogenization of the microstructure. These results demonstrate that improving furnace temperature uniformity facilitates the formation of uniformly sized nanocrystalline grains, thereby effectively enhancing the inductance performance of the cores. This work provides a reliable engineering solution for achieving stable performance in the mass production of high-performance nanocrystalline cores.

Author Contributions

Conceptualization, Junfu Chen and Shaokang Wu; methodology, Shaokang Wu and Likun Li; software, Shaokang Wu and Minshan Pan; validation, Shaokang Wu and Minshan Pan; formal analysis, Junfu Chen and Xiyuan Lan; resources, Junfu Chen and Likun Li; data curation, Shaokang Wu and Minshan Pan; writing — original draft preparation, Junfu Chen and Xiyuan Lan; writing — review and editing, Likun Li; supervision, project administration, Junfu Chen. All authors have read and agreed to the published version of the manuscript.

Artificial Intelligence (AI) Statements

During the preparation of this work, the authors used DeepSeek solely for language polishing and grammar correction of the initial draft. All AI-generated suggestions were critically reviewed and revised by the authors, who assume full responsibility for the final content, figures, data, and interpretation of the conclusions presented in this manuscript. No AI tools were used for data analysis, simulation, experimental design, or scientific conclusion derivation.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interest

The vertical transverse magnetic field heat treatment furnace used in this study was supplied by Guangdong Zhongfu New Material Technology Co., Ltd., and the fabricated nanocrystalline magnetic cores were tested for production validation at the company. All experimental design, data analysis, optimization strategies and research conclusions were completed independently by our research team. Intellectual property rights for equipment retrofits and optimized processes belong solely to our group, with no disputes over economic benefits or patent rights with the above company. Notably, this research received no financial support of any kind from Guangdong Zhongfu New Material Technology Co., Ltd., including research funding, equipment and material expenses, personnel remuneration, travel fees or consulting charges. All research costs are covered by the authors' institutional funds and corresponding research projects.

Funding

The authors acknowledge financial support from Basic and Applied Basic Research Fund of GDAS Foshan Industrial Technology Research Institute (NO. FSY-YF-202512-JS001).

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