

Finite Element Method for Magnetothermal Coupling in Transverse Flux Induction Heating Based on Euler Method

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The finite element method is commonly used to simulate transverse flux induction heating for moving strips. However, the presence of moving parts inevitably leads to mesh deformation or mesh reconstruction, significantly increasing computational effort. In this paper, a magnetothermal coupling finite element calculation method for transverse flux induction heating based on the Eulerian approach is proposed. This method allows for the simulation of transverse flux induction heating in moving strips without requiring mesh reconstruction. Furthermore, bidirectional coupling between the magnetic and thermal fields is incorporated into the calculation process to enhance accuracy. The accuracy and efficiency of the proposed method are validated using a diamond-shaped coil transverse magnetic flux induction heating model, and the results are further verified through experimental data.

Index Terms—Induction heating, magnetothermal coupling, Euler method, finite element method.

I. INTRODUCTION

INDUCTION HEATING (IH) includes two types: transverse flux induction heating (TFIH) and longitudinal flux induction heating (LFIH). Due to its structural characteristics, TFIH is more suitable for heating metal strips and plates, while LFIH is better suited for heating bars and tubes. A key challenge in TFIH research is to accurately simulate the heating process. During this process, the material properties of the heated strip change nonlinearly with temperature, requiring consideration of the bidirectional coupling between the magnetic field and the thermal field. Additionally, since the strip is in motion, simulating the movement introduces mesh reconstruction challenges that must be addressed in the simulation.

At present, two main methods are commonly used to simulate moving parts in the finite element method. The first method involves directly simulating the moving parts using the moving mesh technique, also known as the Lagrangian method [1]. This approach closely approximates real-world conditions; however, it has the drawback of causing mesh deformation or requiring mesh reconstruction, which significantly increases computational effort and may even reduce accuracy. The second method replaces continuous motion with discrete steps [2]. In this approach, the continuous motion of the strip is divided into multiple discrete time steps, with magnetic-thermal coupling simulations performed at each step. The result from each time step is then used as the initial condition for the next, continuing until convergence is achieved. While this method avoids mesh deformation or reconstruction, it requires manual adjustment of the relative positions between models at each step and necessitates manually transferring the temperature data from the previous step to the next, which complicates the fully automated optimization process.

In this paper, a finite element calculation method based on the Euler method is proposed to address these challenges. The method draws from fluid dynamics calculations, utilizing a fixed model framework to simulate the motion of the fluid field. In this approach, the model framework remains stationary while the strip material flows continuously from

one side to the other. Meanwhile, the moving parts are effectively replaced by stationary ones, thereby transforming the original transient problem into a steady-state problem.

II. TFIH MODEL AND EULER METHOD

A. TFIH model

In this paper, an TFIH model with a diamond coil structure is used as the research vehicle. Fig. 1 shows the model consists of two sets of coils and a pair of magnetic cores. The strip passes between the magnetic poles at a constant speed. To facilitate calculations, a quarter-model approach is adopted instead of using the full model, leveraging the symmetry of the system.

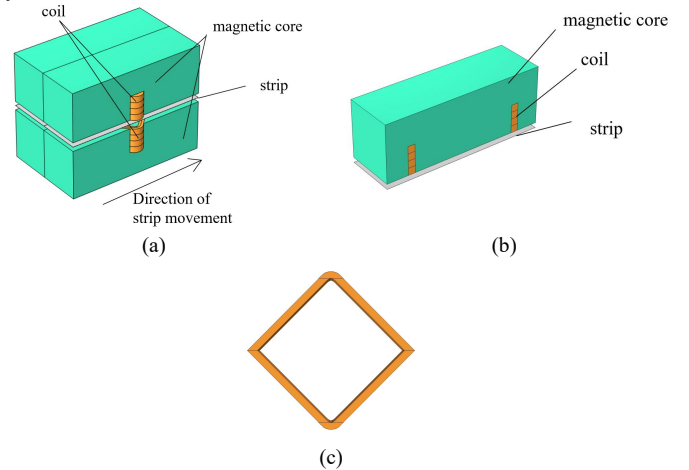


Fig. 1. TFIH model, (a) full model, (b) quarter model, (c) diamond coil.

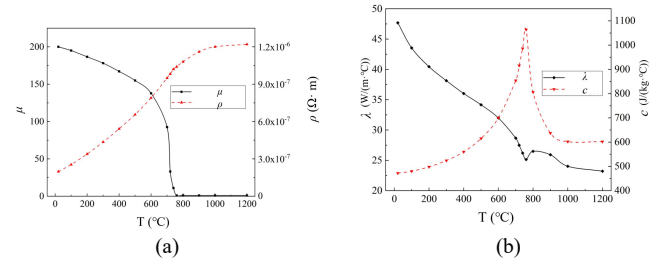


Fig. 2. Characteristic curve of strip material, (a) variation of relative magnetic permeability μ and electrical resistivity ρ with temperature, (b) variation of thermal conductivity λ and specific heat capacity c with temperature.

The material properties of the strip change nonlinearly with increasing temperature, and the characteristic curve is shown in Fig. 2. It can be observed that these four parameters exhibit nonlinear variations with temperature, particularly near the Curie point. Therefore, during the magnetic-thermal coupling calculations, it is essential to account for the bidirectional coupling between the magnetic and thermal fields. Specifically, for each thermal field calculation, the updated material properties corresponding to the current temperature must be used for the subsequent magnetic field calculation. This process is repeated iteratively until convergence is achieved.

B. Euler method

The study object of TFIH is a heated strip undergoing continuous translational motion, which must be accurately simulated in the analysis. The Euler method, originally used to describe fluid fields, tracks the physical quantities of fluid particles as they flow through each spatial point in the fluid field. These quantities are functions of both time and spatial position, ultimately providing the state of the entire fluid field. In TFIH, the strip can be treated as a fluid moving in a single direction, where all particles move along the same direction of motion. Since the effects of laminar and turbulent flow are not considered, this simulation can be simplified by adding a velocity term to the heat source in the thermal field calculation. The Fourier heat conduction equation for calculating the temperature field $T(x, y, z, t)$ is as follows,

$$\frac{\partial(cpT)}{\partial t} = \nabla \cdot (\lambda \nabla T) + Q - v \cdot \nabla (cpT) \quad (1)$$

where c is the specific heat, λ is the thermal conductivity, ρ is the density, and v is the velocity, the temperature T is a function of the three-dimensional coordinates (x, y, z) and time t , and Q represents the heat source.

III. SIMULATION RESULTS AND COMPARATIVE ANALYSIS

Three methods were used to calculate the model under the same computational configuration. Meanwhile, the temperature distribution curves of the strip at the outlet of the heater are shown in Fig. 3, which demonstrate that the results from the three methods are almost identical.

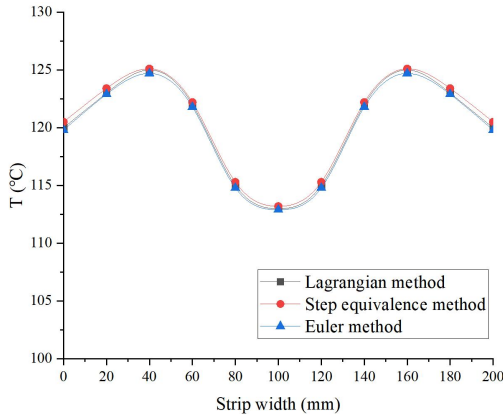


Fig. 3. Temperature distribution curves of the strip at the outlet of the heater.

The comparison of simulation times is shown in Table I. It can be observed that the Lagrangian method requires the longest time, followed by the step equivalence method, while

the Euler method takes the shortest time. The Euler method greatly improves computational efficiency while ensuring accuracy.

TABLE I
PERFORMANCE COMPARISON OF THREE METHODS

	Lagrangian method	Step equivalence method	Euler method
FEA time (h)	12.5	3.2	0.1

IV. EXPERIMENTAL VERIFICATION

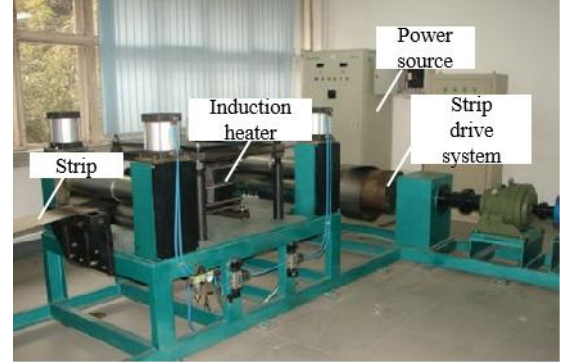


Fig. 4. Diamond coil transverse flux induction heating system.

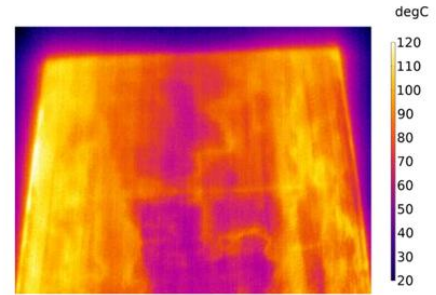


Fig. 5. Diamond coil transverse flux induction heating system.

Fig. 4 shows the diamond coil TFIH system used in the experiment, which includes the induction heater, the strip transmission system, the power supply and the strip. The temperature distribution of the strip obtained from the experiment is shown in Fig. 5.

V. CONCLUSION

The magnetic thermal coupling calculation method based on the Euler method proposed in this paper can greatly improve the calculation efficiency while ensuring the calculation accuracy compared to other methods. Due to the overall and automated nature of its calculation process, this method provides convenience for optimizing the design of TFIH devices in the future.

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