Induction Heating Devices with A Moving Inductor of Low and High Frequency

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Abstract:This work presents a numerical simulation model using comsol multiphysics developed for coupling the electro magneto and thermal phenomena taking place in induction electromagnetic heating devices with a moving inductor. All three electro magneto and thermal models are time dependent and take full account of the electro magneto and thermal non linear effects especially with ferromagnetic and non ferromagnetic materials. The numerical simlation which has been used to solve the electro magneto and thermal problem is based on a finite element method with a comsol multiphysics in the moving inductor, workpiece and air. The maxwell's equations and the heat transfer equations are solved in the moving inductor and workpiece using an electromagnetic model of low and high frequency. Non-lineair model has been applied successfully to several positions of inductor and workpiece.By taking these factors into consideration, thermal comfort can be effectively managed in induction heating, ensuring safe and efficient operation for both operators and equipment.

Key words:induction heating,thermal comfort, maxwell's equations, Comsol multiphysics,

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1. Introduction

Induction heating is a process that involves the use of electromagnetic fields to generate heat within a conductive material [1].. This process is widely used in various industries, including automotive, aerospace, and manufacturing. One of the key components of induction heating is the inductor, which is responsible for generating the electromagnetic field. Traditionally, the inductor is stationary, and the workpiece is moved into and out of the field. However, in recent years, there has been a growing trend towards using a moving inductor instead. In this article, we will discuss the advantages of using a moving inductor in induction heating applications [2].

Low-frequency induction heating devices with a moving inductor are used for heating large metal objects, such as billets, slabs, and bars. The inductor moves along the length of the object, heating it uniformly and efficiently. The low-frequency induction heating process is ideal for heating objects that have a high electrical resistance, such as stainless steel and titanium alloys. The process is also used in the production of rails, pipes, and other large metal objects that require uniform heating.

High-frequency induction heating devices with a moving inductor are commonly used for heating small metal objects, such as bolts, nuts, and screws. The inductor moves rapidly over the objects, heating them quickly and efficiently. The high-frequency induction heating process is ideal for heating objects that have a low electrical resistance, such as copper and aluminum alloys. The process is also used in the production of small metal parts, such as gears, bearings, and connectors.

induction heating devices with a moving inductor offer an efficient and versatile heating process with minimal heat loss and energy consumption for various industries. The use of low-frequency and high-frequency induction heating devices with a moving inductor allows for the efficient and uniform heating of large and small metal objects, respectively. The process offers several advantages over other heating methods, including high efficiency, controllability, and versatility. Induction heating can generate high levels of heat, which can create uncomfortable working conditions for operators and workers. The heat generated by induction heating can cause discomfort, fatigue, and even heat-related illnesses, such as heat exhaustion and heat stroke. Therefore, ensuring thermal comfort in induction heating is essential for maintaining worker safety, productivity, and overall well-being[3].

Several factors affect thermal comfort in induction heating, including the type of heating equipment used, the size and shape of the heated object, the duration of the heating process, and the ambient temperature and humidity.Several studies have been conducted to evaluate the thermal comfort of workers in induction heating. Most of these studies have focused on the effect of the heating time and the distance between the worker and the heating source on thermal comfort. For instance, a study by Rowe et al. [4] investigated the thermal comfort of workers in a steel mill during induction heating. The results showed that the thermal sensation increased with increasing heating time and decreased with increasing distance between the worker and the heating source. Another study by Bay et al. [5] evaluated the thermal comfort of workers in a forging workshop during induction heating. The study found that the thermal sensation was strongly influenced by the heating time, with longer heating times leading to increased discomfort. The study also showed that the distance between the worker and the heating source had a significant effect on thermal comfort, with closer distances leading to higher discomfort. Other factors that have been found to influence thermal comfort in induction heating include the type of workpiece, the power output of the heating source, and the ambient temperature. For instance, a study by Kagimoto et al. [6] investigated the thermal comfort of workers in a forging workshop during induction heating of different types of steel. The study found that the thermal sensation was significantly influenced by the type of steel, with higher discomfort reported for harder steels.

To ensure thermal comfort in induction heating, several strategies can be used, including proper design and implementation of heating systems, the use of appropriate personal protective equipment, and engineering controls. For instance, heating systems can be designed to incorporate ventilation and cooling systems to reduce the ambient temperature and humidity levels. Personal protective equipment, such as heat-resistant gloves, aprons, and face shields, can also be used to protect operators from the heat generated by induction heating. Engineering controls, such as automated heating systems, can be used to minimize operator exposure to high levels of heat [7,8].

Finally, the induction heating process itself should be carefully controlled to minimize temperature fluctuations and ensure consistent heating. This can be achieved through the use of temperature sensors and feedback control systems, which can adjust the heating parameters in real-time to maintain a stable and comfortable working environment [9,10]

2. Modeling and Analysis of Structural Geometry

An induction heating system consists of several components that work together to generate and apply electromagnetic fields to heat a conductive material. The key components of an induction heating system are: Power supply, Induction coil, Workpiece, Cooling system andControl system [11].

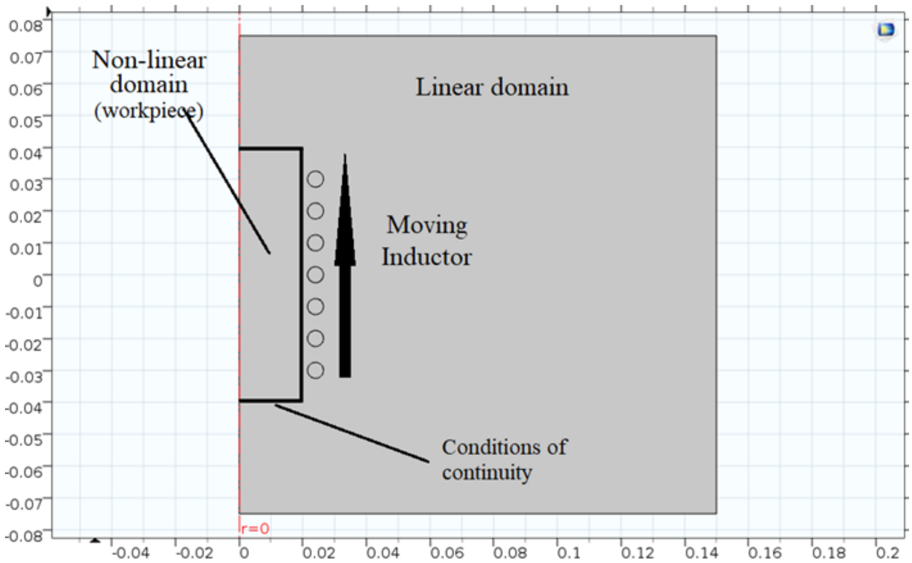


Figure 1. Solution domains for 2D induction heating analysis.

Overall, the geometry of an induction heating system is designed to maximize the efficiency of the electromagnetic field and ensure that the workpiece is heated evenly [12,13,14]. The size and shape of the induction coil, as well as the distance between the coil and the workpiece, are critical factors that determine the effectiveness of the system. Fig 1 and fig 2 shows the geometry and the initial location of the inductor.

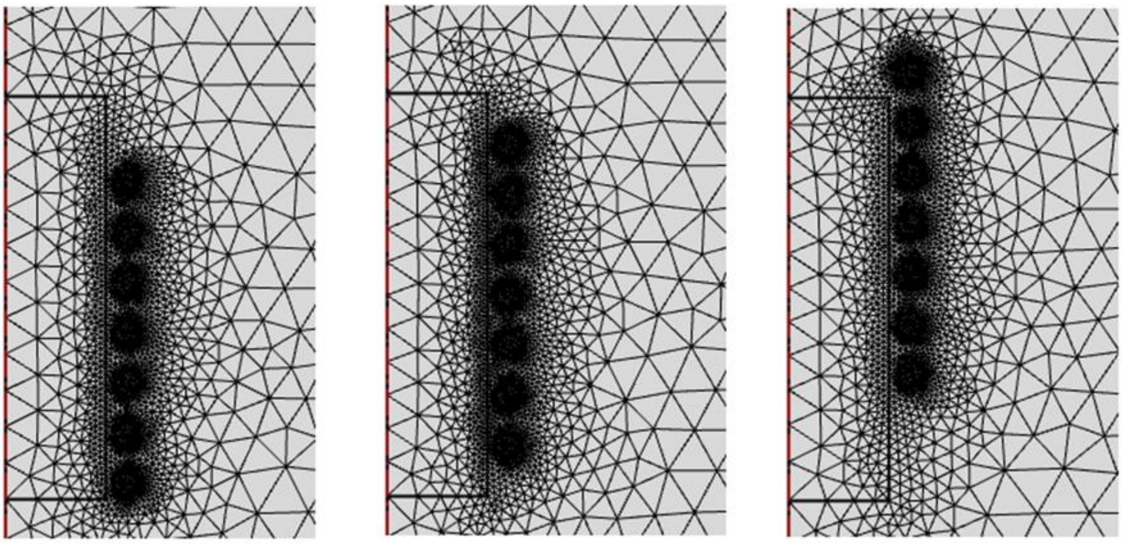


Figure 2. Mesh generations for the moving inductor in three positions: (a) initial, (b) medium and (c) final stations.

In the case of induction heating, Maxwell's equations are used to calculate the electromagnetic field produced by the induction coil, which is responsible for generating eddy currents in the conductive material. The eddy currents, in turn, generate heat due to the resistance of the material, which can be described by the heat conduction equation.In addition to the electromagnetic and thermal phenomena, other physical effects may also need to be considered in the modeling of induction heating processes, such as mechanical deformation[15,16,17],

$$\vec{\nabla} \cdot \vec{D} = r \quad (1)$$

$$\vec{\nabla} \cdot \vec{B} = 0 \quad (2)$$

$$\vec{\nabla} \times \vec{E} = \frac{\partial \vec{B}}{\partial t} \quad (3)$$

$$\vec{\nabla} \times \vec{H} = \vec{J} + \frac{d\vec{D}}{dt} \quad (4)$$

The Joule heat source for induction heating is used to calculate the amount of heat generated by the eddy currents induced in the material being heated. It is expressed as [18,19]:

$$Q = \frac{1}{2}\vec{J} \cdot \vec{E} \quad (5)$$

The heat transfert equation for induction heating can be expressed as [20]

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p u \cdot \nabla T - \nabla \cdot (k \nabla T) = Q \quad (6)$$

In this configuration, the moving inductor induces a magnetic field in the cylindrical conductor, which in turn generates an electric current. The direction of the induced current depends on the direction of the magnetic field and the motion of the inductor [21].

$$\vec{J} = \sigma(\vec{E} + \vec{v} \times \vec{B}) \qquad (7)$$

Introducing Lenz's law, the modified equation becomes (equation (4)) [22]:

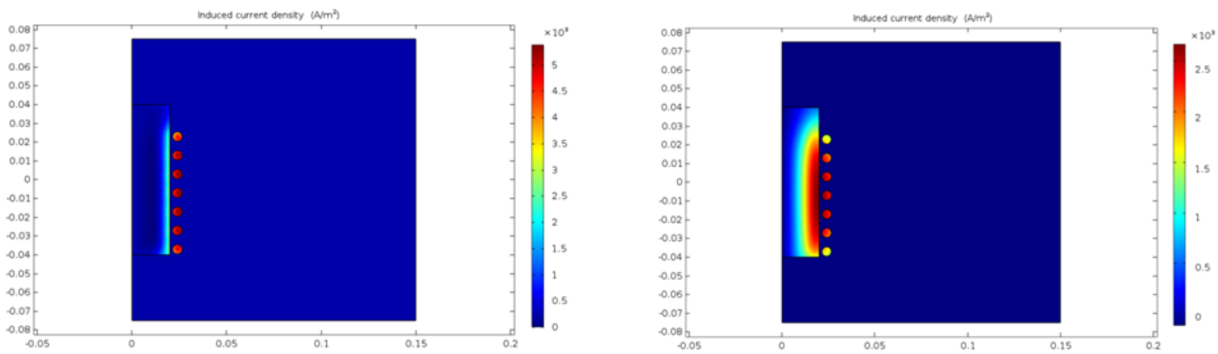
$$\sigma \frac{\partial \vec{E}}{\partial t} + \vec{\nabla} \times \left(\frac{1}{\mu} \vec{\nabla} \times \vec{E}\right) - \sigma \vec{v}\, \overline{\times \vec{\nabla}} \times \vec{E} = -\frac{\partial \vec{J}}{\partial t} \qquad (8)$$

In cylindrical coordinates, the equation of the electric field can be written as [23]:

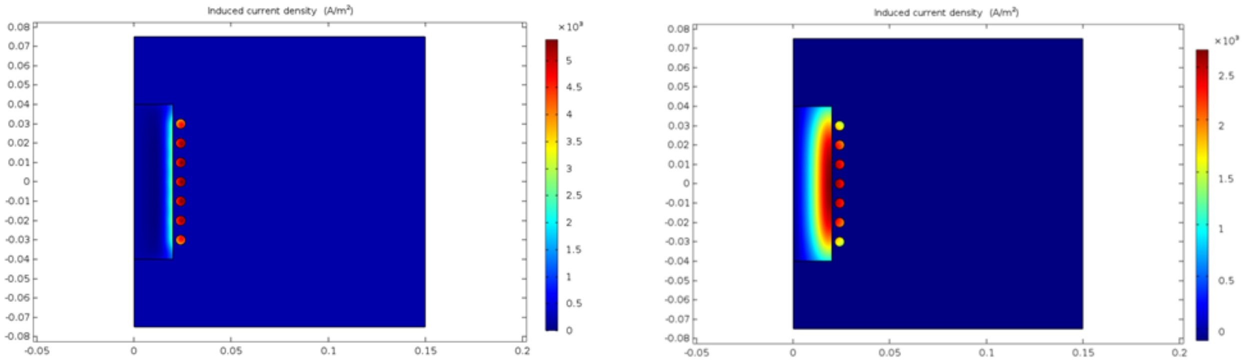
$$\sigma \frac{\partial \vec{E}}{\partial t} - \vec{\nabla} \times \left(\frac{1}{\mu} \vec{\nabla} \times \vec{E}\right) + \frac{1}{\mu} \frac{\vec{E}}{r^2} - \frac{\partial}{\partial r}\left(\frac{1}{\mu}\right) \frac{E}{r} - \sigma \overrightarrow{v_z} \frac{\partial}{\partial z} \vec{E} = -\frac{\partial \vec{J}}{\partial t} \qquad (9)$$

3. Analysis and Interpretation of Results

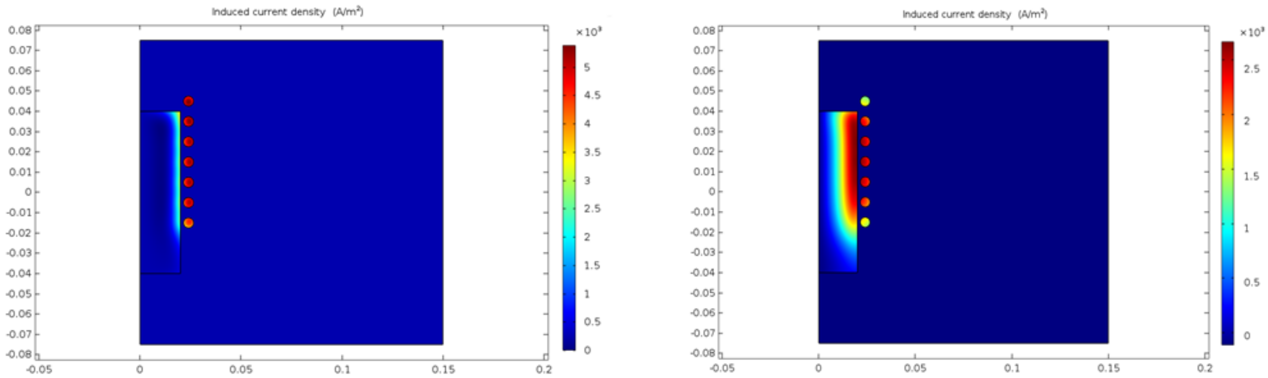
The frequency of the alternating current used in induction heating is an important parameter that affects the heating process. In the time-harmonic regime, the current and voltage in the heating coil vary sinusoidally with time. The frequency of the alternating current determines the rate at which the magnetic field changes and, therefore, the rate at which energy is transferred to the workpiece. The optimal frequency for a given application depends on several factors, including the material properties of the workpiece, the desired heating rate and temperature, and the size and shape of the workpiece. In general, higher frequencies are preferred for smaller workpieces and for applications requiring rapid heating, while lower frequencies are preferred for larger workpieces and for applications requiring slower, more uniform heating. Fig 3 and fig 4 show the current density and the magnetic flux density at a frequency of 300 Hz (right) and 1000 Hz (left) in three positions, respectively



(a)



(b)



(c)

at f = 1000 Hz   at f = 300 Hz

Figure 3. The current density for (a) initial, (b) medium and (c) final stations.

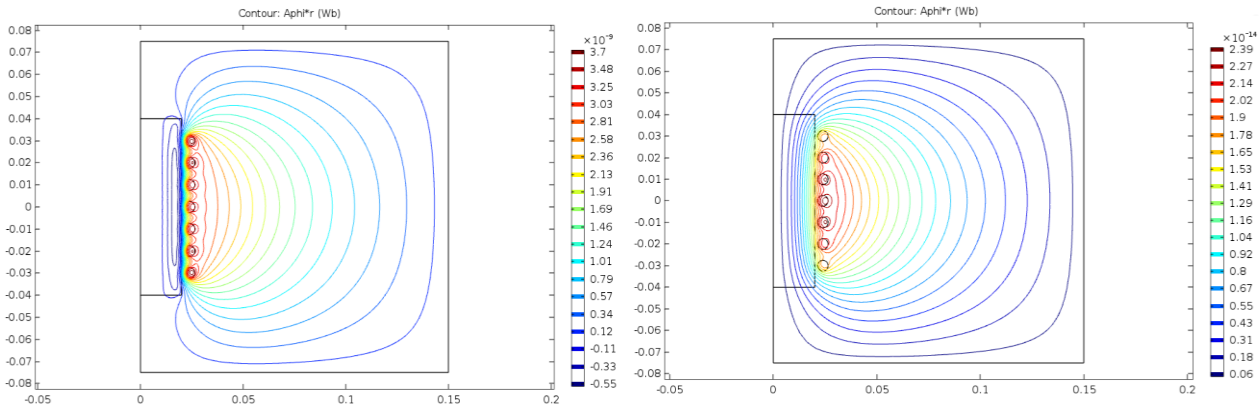


Figure 4. The magnetic flux at f = 300 Hz (right) and f = 1000 Hz (left).

The step response of system can provide valuable information about the heating process, such as the time required to reach a steady state temperature and the effect of the skin effect on the heating process. This information can be used to optimize the design of induction heating systems for specific applications.(see Fig. 5).

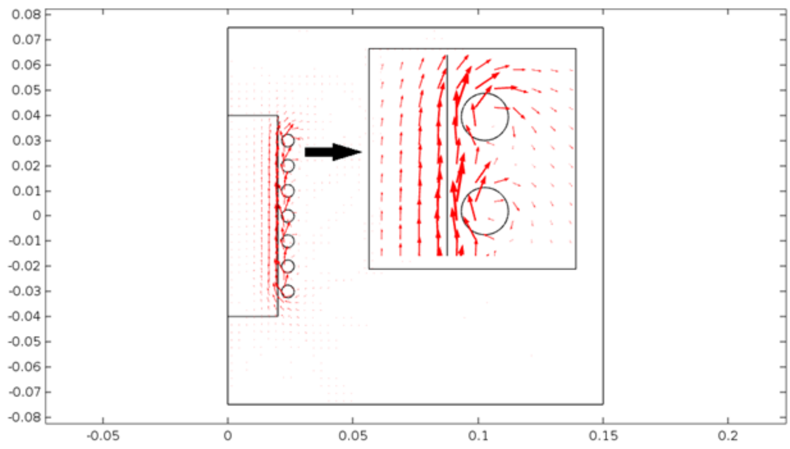


Figure 5. The induced current density (arrow plot) during the transient study.

The rate of temperature increase (has increased from 293 K to 346 K, during 10s (see Fig. 6). depends on several factors, including the frequency and power of the induction heating system, the size and shape of the workpiece, and the material properties of the workpiece. In general, higher frequencies and powers will result in faster heating rates, while larger and thicker workpieces will take longer to heat up.

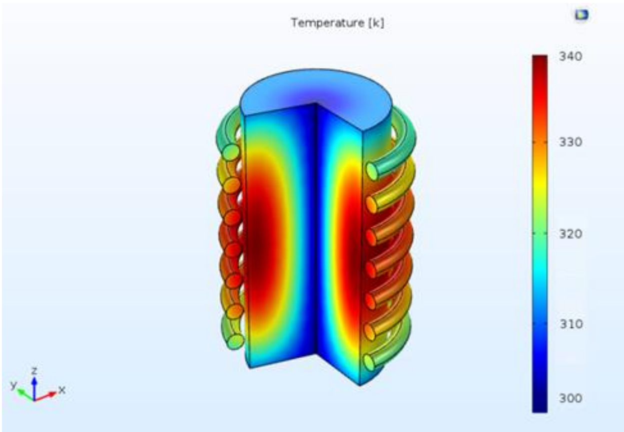


Figure 6. Temperature distribution after 10 s.

It is important to monitor the temperature of the workpiece during induction heating to ensure that it does not overheat and cause damage to the material or the induction heating system. Various temperature monitoring techniques can be used, such as infrared thermography or thermocouples, to measure the temperature of the workpiece during the heating process

Electromagnetic forces play a critical role in induction heating, as they are responsible for electromagnetic Induction in the workpiece and generating the heat.The electromagnetic forces involved in induction heating are complex and can be affected by several factors, including the frequency and power of the induction heating system, the shape and size of the workpiece, and the material properties of the workpiece. The strength and direction of the electromagnetic fields can also be affected by the position and orientation of the workpiece relative to the induction heating coil. In addition to generating heat, electromagnetic forces can also cause mechanical stresses and strains in the workpiece, particularly at high frequencies and powers. These forces can lead to microstructural changes in the material, such as grain growth and recrystallization, which can affect the properties and performance of the workpiece.

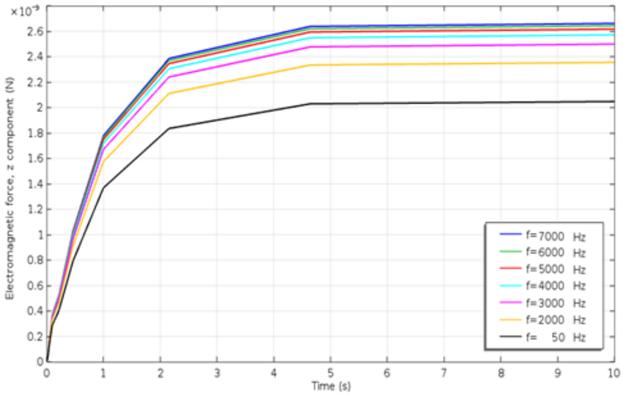


Figure 7. Electromagnetic force variation with frequency and time in induction heating.

The power in induction heating is directly proportional to the square of the frequency frequency (see Fig. 8).. This means that as the frequency increases, the power also increases exponentially. Therefore, the choice of power and frequency in induction heating depends on the specific material and application requirements. Factors such as the size and shape of the part, the desired heating rate, and the desired depth of heating all need to be considered when selecting the optimal power and frequency settings.

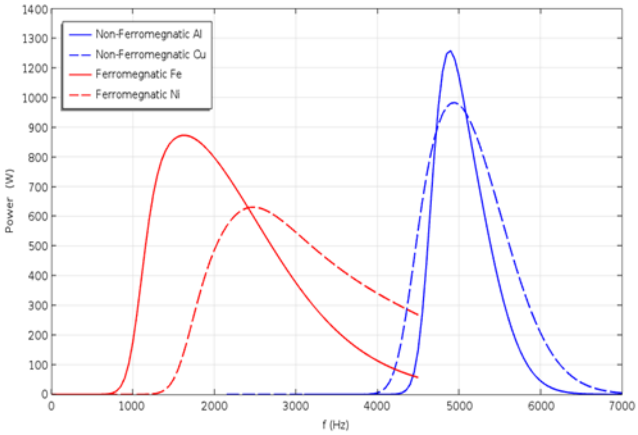


Figure 8. Induction heating performance: ferromagnetic vs. non-ferromagnetic materials.

Ferromagnetic materials are commonly used in induction heating applications because of their high efficiency and ability to rapidly heat up. Non-ferromagnetic materials are typically used in applications where precise temperature control is important, the choice between ferromagnetic and non-ferromagnetic materials for induction heating depends on the specific application and desired outcome

4. Conclusion

the thermal comfort in induction heating with a moving inductor using COMSOL can be optimized by carefully designing the geometry of the inductor, controlling the power input, and selecting the appropriate cooling mechanism. The simulation results show that the temperature distribution can be controlled to ensure that the target material is heated uniformly and efficiently, while minimizing the risk of overheating or thermal damage to surrounding components. Moreover, the use of COMSOL simulation software offers a powerful and flexible tool for predicting and optimizing the thermal performance of induction heating systems, thereby enabling more accurate and efficient design and operation.

The choice of material for induction heating depends on its electrical conductivity and magnetic permeability properties. Metals are the most commonly used materials in induction heating applications, followed by plastics, ceramics, composites, glass, and food products. The properties of the material being heated should be carefully considered when designing an induction heating system to ensure optimal performance and efficiency.

The future of induction heating technology is very promising. With the continuous development of science and technology, induction heating technology will continue to improve and innovate, and will play an increasingly important role in various industries.

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