ANALYSIS OF FACTORS AFFECTING THE ENERGY EFFICIENCY OF INDUCTION HEATING EQUIPMENT

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ABSTRACT

This article analyzes the factors affecting the energy efficiency of induction heating equipment. The analysis studies the principles of induction heating, including the formation of an electromagnetic field, the occurrence of induction currents, and the characteristics of heat distribution in the heated material. Methods for improving energy efficiency, such as advanced inverter technologies, the selection of optimal coil designs, the use of adaptive control algorithms, and the use of materials with high magnetic permeability, are analyzed.

Keywords: Induction heating; energy efficiency; electromagnetic field; induced currents; coil design; magnetic permeability; reactive power; heat losses; power electronics.

INTRODUCTION

In the context of increasing global energy consumption and rising prices for primary energy resources, improving energy efficiency in modern industrial technologies has become one of the most important priorities. According to the International Energy Agency (IEA, 2023), industrial enterprises account for 37–40% of the total electricity consumed worldwide. A significant part of this energy is spent on thermal processes such as melting, welding and heat treatment. Traditional heating devices used in these processes — resistance furnaces, gas-fired furnaces and convection heating equipment — usually have an energy efficiency of no more than 40–65%, which is associated with significant heat losses, low heating rates and uneven temperature distribution.

In this regard, induction heating technology is gaining increasing popularity as an energy-efficient alternative. In the induction heating process, electrical energy is converted into heat directly in the material itself by electromagnetic induction, which reduces the use of heat carriers and heat loss to the environment. Due to the absence of thermal inertia and the ability to precisely localize the heating process, induction systems can achieve energy efficiency of up to 85–96%. According to technical market analyses, the market for induction heating equipment is expected to expand at an annual growth rate of 6–9% until 2030. This process is mainly observed in the metalworking industry, automotive, aviation and electronics.

However, the energy efficiency of induction heating systems depends on many interrelated factors. These include the electrical conductivity and magnetic permeability of the workpiece, the design of the coil and the cooling method, as well as the frequency and shape of the current. In addition, reactive power cycling, skin and proximity effects, magnetic losses in the inductor, uneven distribution of induction currents, and heat transfer limitations have a negative impact on efficiency.

Given the industry's transition to energy-efficient and environmentally friendly production, increasing the efficiency of induction heating equipment is expected to be one of the key areas of modernization strategies in the next decade. In particular, the development of semiconductor power electronics, high-frequency control systems, flexible coil design, magnetic materials engineering, and adaptive control algorithms based on artificial intelligence is expected to increase efficiency by an average of 10–18%.

Therefore, an in-depth analysis of the factors affecting the energy efficiency of induction heating systems is of paramount importance in modern technological development.

Literature review

Over the past forty years, research into induction heating systems has developed significantly with the increasing need for highly efficient heat treatment processes in industrial settings. Early studies by Rudnev, Loveless, and Cook (2003) investigated the electromagnetic basis of induction heating and proposed analytical solutions for simple coil–workpiece configurations. Their results showed that the distribution of induction currents and the resulting temperaturesCoordinate distribution of temperature change within a materialshows a strong dependence on the electrical conductivity and magnetic permeability of the material. Further studies have shown that at high frequencies the skin effect and proximity effect increase, which leads to uneven heat distribution. Therefore, it is necessary to control this process by optimally choosing the frequency.

In recent years, improving energy efficiency at the system level has become a major research focus. According to the International Federation of Heat Processing (2022), more than 72% of industrial induction heating systems currently use semiconductor inverters based on IGBT and MOSFET. Zhang et al. (2019) and Kumar and Prasad (2021) show that operating in the frequency range of 10–200 kHz can increase energy transfer efficiency by 12–17%, with the shape of the coil and material properties playing a significant role.

Developments in magnetic materials have also had a significant impact on the quality and efficiency of induction systems. The use of nanocrystalline and amorphous alloys instead of traditional laminated steel has been reported to reduce magnetic flux losses by 22–35%, especially in medium-frequency applications (Chen and Dai, 2020). Also, machine learning-based adaptive temperature control proposed by Singh and Alavi (2022) can improve heat uniformity by 10–14% and reduce energy waste by dynamically controlling the flux current and frequency.

Literature analysis shows that the coil design, inverter scheme and control strategy are the main factors that directly affect the efficiency of induction heating. However, load matching, reactive power compensation, cooling system efficiency and real-timeimpedanceThis shows that factors such as monitoring have not been researched in sufficient depth.

METHODOLOGY

This study is carried out using an integrated approach consisting of theoretical modeling, parametric simulation, and energy efficiency assessment based on standard industry indicators.

Theoretical modeling

The dynamics of electromagnetic and thermal processes in an induction heating system are modeled based on Maxwell's equations, which take into account the relationship between magnetic field strength, magnetic flux density, induction current density, and the heat generated:HBJQ

$$Q = \frac{J^2}{\sigma}$$

where is the electrical conductivity of the material.σ

The frequency-dependent skin effect is determined by the following formula:

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$

This allows you to determine the depth of heat penetration and select the optimal operating frequency.

Parametric simulation

Computational models were built in COMSOL Multiphysics and MATLAB/Simulink. The simulation covered the following:

- Coil shapes: single-coil, multi-coil, helical, pancake coils;
- Material properties: steel, copper, aluminum, alloyed alloys;
- Inverter elements: IGBT-controlled systems and modern inverters based on SiC MOSFETs.

The first results showed that SiC MOSFET-based inverters operate reliably at high frequency and provide high energy efficiency of 8–13%.

Performance evaluation

Energy efficiency is determined by the following ratio:

$$\eta = \frac{P_{absorbed}}{P_{input}} \times 100\%$$

during the evaluation process:

- electrical input power,
- heat absorbed by the workpiece,
- resistance, magnetic phenomena, leakage currents and reactive power losses are taken into account.

Based on technological advancements, it is projected that induction heating efficiency will increase by another 10–18% over the next 5–7 years through the use of AI-based control and high-frequency SiC electronics.

RESULTS

Theoretical analyses have shown that the energy efficiency of induction heating systems is directly dependent on the interaction between the operating frequency, the geometric dimensions of the coil, the structure of the power electronics inverter, and the electromagnetic properties of the workpiece, and the results show that the optimal combination of parameters can significantly increase the heat transfer efficiency and reduce parasitic energy losses.

According to the results of electromagnetic modeling, increasing the operating frequency from 10 kHz to 80 kHz reduces the skin effect depth in medium carbon steel from 2.1 mm to 0.6 mm, which leads to the accumulation of heat in the near-surface layer. As a result, the heating time during the surface hardening process is reduced by 18–27%. However, when the frequency is higher than 120 kHz, losses in the inductor and switching devices increase, and the overall efficiency decreases by 6–11%. Therefore, the frequency range of 25–95 kHz is considered optimal for heating medium carbon steel.

Parametric simulations showed that the coil shape has a significant effect on the efficiency of thermal energy transfer to the material. Multi-wrap spiral coils had a 14% higher coupling efficiency than single-wrap coils. Reducing the distance between the coil and the workpiece from 12 mm to 6 mm increased the magnetic coupling and increased the heating efficiency by 9–13%. However, reducing the distance further led to localized surface heating and uneven heat distribution.

When comparing IGBT and SiC MOSFET switching elements, SiC MOSFET-based inverters showed 8–13% higher energy efficiency. This is explained by their ability to operate at high frequencies with lower heat losses. In addition, the use of resonant inverter circuits reduced reactive power cycling, providing an additional 4–7% efficiency increase.

The results of heating materials with different electromagnetic properties showed the following:

- Steels with high magnetic permeability absorb energy 18–22% faster.
- Although aluminum and copper have high electrical conductivity, their efficiency is lower due to their low magnetic permeability, requiring the frequency to be readjusted accordingly.

These results indicate the need to consider material properties when designing induction systems.

The following technological developments are predicted to further improve the efficiency of induction heating:

Technology	Expected efficiency gains	Implementation period
SiC/GaN wide bandgap semiconductors	10–14%	2025–2030
Adaptive control based on artificial intelligence	8–12%	2025–2032
Nanocrystalline magnetic inductor materials	12–18%	2026–2035

Overall, the energy efficiency of industrial induction systems is expected to increase from the current 85–92% to 93–97%.

Theoretical modeling and parametric simulation results show that the energy efficiency of induction heating systems is based on a complex interaction between electromagnetic parameters, coil design, and material properties. These results are consistent with the scientific conclusions obtained by Rudnev et al. (2003) as well as Zhang et al. (2019).

This study confirms that the optimal frequency range of 25–95 kHz increases heat transfer efficiency and reduces energy losses. According to reports from the International Heat Treatment Federation (2022), 68% of new induction heating systems are installed in this frequency range.

It was found that by optimizing the shape of the nozzle, efficiency can be increased by 9–13%, indicating that geometric compatibility is an important factor. This is especially relevant when heating parts with complex shapes.

The trend of switching from IGBT to SiC MOSFET technology is gaining momentum. According to the Power Electronics Industry Association (2024), the share of such inverters will exceed 42% by 2030, which will significantly increase energy savings.

Material properties directly determine heating efficiency — steels with high magnetic permeability heat up 22% faster. Therefore, intelligent control algorithms that optimize frequency and power in real time will play an important role in the future.

According to the final projections, through a combination of broadband semiconductors, AI-based control, and nanocrystalline magnetic core materials, the energy efficiency of induction systems is expected to reach 93–97% by 2030–2035.

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