



## The Effect of Workpiece Geometry on Heat Transfer in Induction Heating

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### Abstract

Induction heating is a modern and rapid heating method that enables the heating of conductive materials through high-frequency current using a non-contact and directed electromagnetic field, where the heat is delivered directly to the workpiece to be heated. One of the important factors affecting energy transfer in induction heating systems is the geometry of the workpiece used as the heater. In this study, the effect of three different internal insert geometries, while maintaining the same external geometry, on total heat transfer during induction heating of a fluid flowing inside a pipe was investigated. The experimental study was carried out using a 25-kW professional induction machine operating with a 3-phase, 380 V power supply in a medium-scale industrial facility. Convective heat transfer values were calculated based on experimental data. Results showed that the insert with a helical internal geometry exhibited the highest convective heat transfer.

**Keywords:** *Induction heating, Fluid heating, Workpiece geometry, Convection, Energy analysis*

### 1. Introduction

Induction heating, based on the principle of electromagnetic induction, is a process that requires no contact, provides high energy efficiency, and features a high heating rate over a short period. Some of the advantages of induction heating include achieving precise temperatures, enabling localized heating control, contactless heating, ensuring high occupational safety, preserving material properties, high repeatability, and providing process control. Induction heating is a modern heating method that is becoming increasingly widespread today. In industrial applications, induction heating plays a critical role in metal melting, surface hardening, annealing, brazing, compression, pipe heating, pre-heating before rolling, and advanced manufacturing technologies. Today, induction heating is increasingly adopted as a modern alternative to conventional heating in numerous industrial applications such as metal melting, surface hardening, annealing, brazing, shrink-fitting, tube heating, pre-rolling heating, and advanced manufacturing technologies. [1–3]. Among the main reasons for this are the ability of induction systems to generate heat only in the target area, low heat losses, minimum thermal load on the environment, easy control, the ability to operate in high-frequency ranges, and the absence of occupational safety risks. Technical evaluations by companies such as CEIA,

Ambrell, and Eldec indicate that induction has become a standard solution in industrial applications, particularly for energy efficiency and rapid heating needs [4–6].

One of the most critical components in the induction heating process is the geometry of the heating element and the coil. The heating coil is the basic element that generates the system's magnetic field, and the intensity of the induced currents on the material is directly related to parameters such as the coil's number of turns, form, frequency, distance to the material, and geometric placement [7, 8]. Zinn and Semiatin (2002) state that the coil geometry is decisive on the magnetic flux density, and that heat transfer rates can seriously differ with changes in the coil–workpiece coupling [9]. Similarly, Rudnev (2003) emphasized that the air gap between the coil–workpiece (charge), the type of winding, and the geometry are among the most critical parameters determining system efficiency [8, 10]. Therefore, optimizing the coil geometry is considered one of the primary ways to increase system efficiency in modern induction systems.

In recent years, the literature contains many analytical, numerical, and experimental studies examining the effect of coil geometry on heat transfer. Coupling geometry is decisive on thermal efficiency, and

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optimizing the coil's internal geometry can increase the total heat transfer by 15–30% [9, 11]. Magnetizer geometry affects the eddy current density on the material surface by changing the local magnetic field distribution, thus altering the heating rate [10, 12]. The electromagnetic–thermal coupling in induction heating shows high sensitivity to geometric parameters, indicating the critical role of geometry in the design phase [10].

The main objective of this study is to experimentally compare the heat transfer performance of the heating element to the fluid passing through the workpiece (charge) for three different internal geometries (insert structures) having the same external geometry. Thus, the effects of the electromagnetic field created between the coil and different workpiece internal geometries, and their effects on fluid convective heat transfer, were investigated. The experimental studies were carried out with a 25-kW industrial induction machine operating on 3-phase, 380V. Convective heat transfer properties were determined by positioning different insert geometries within the water flow, and heat transfer calculations were made based on temperature differences and flow rate measurements. The results show that the helical (spiral) form insert has the highest heat transfer among the three different internal geometries. This finding is related to the internal geometry, both increasing the electromagnetic flux density and increasing the contact surface area of the fluid. Within the scope of this article, first, the theoretical background of induction heating is presented, followed by the explanation of the experimental setup and measurement method, and finally, comparative heat transfer analyses of the three different internal geometries are provided. In the last section, the findings are evaluated in relation to the literature, and suggestions for system design are presented.

## 2. Basic Concept and Calculation of Heat Transfer Induction Heating

Induction heating is based on the principle of heat generation on the outer surface of a conductive pipe through a magnetic field. The high-frequency electromagnetic field created by the coil leads to eddy currents and hysteresis effects on the pipe surface, causing the pipe to heat in a short time [13, 14]. In this study, the coil geometry, applied power, frequency, and external heating conditions were kept constant; only different geometric insert structures placed on the internal surface of the heated pipe were used as the experimental variable. Thus, the effect of the internal

flow path shape on the process of transferring heat to the liquid was investigated.

### 2.1. Principle of Pipe Induction Heating

In induction heating, energy is converted into heat through eddy currents generated on a conductive material. Since the magnetic field changes with time, the intensity of the currents induced on the pipe surface is determined by the coil's frequency and the pipe material properties [15]. Since all experiments in the study were conducted with the same induction machine, the heat generation on the outer surface of the pipe is the same in every experiment. This heat generated on the outer surface of the pipe is transferred to the water flowing through it via convective heat transfer. Therefore, the experimental comparison examines how the heat transfer changes, not the heat generation.

### 2.2. Workpiece Inside Insert Concept and Fluid Behavior

An insert is defined as an internal structure placed inside the pipe through which the fluid passes, changing the flow shape, velocity distribution, and surface contact. The primary heat transfer effect of inserts in the literature is explained by three main mechanisms:

- a) Change in Flow Regime (Laminar to Turbulent): Inserts disrupt the fluid's velocity profile and force the flow to rotate, swirl, or change direction. Increased mixing and turbulence significantly increase the heat transfer coefficient near the wall [16, 1].
  - b) Increased Heat Transfer Surface Area: The insert geometry can increase the contact of the fluid with the inner surface of the pipe. Designs that particularly expand the surface area or present more surface to the liquid directly increase the amount of heat transfer ( $Q$ ) [2].
  - c) Directing the Flow to the Wall Region: Since heat transfer occurs most intensely near the wall, inserts can ensure more effective heat transfer by directing the flow towards the wall [3].
- Therefore, each insert geometry affects the liquid heating performance at a different level.

### 2.3. Insert Geometry-Dependent Heat Transfer Mechanisms

Inserts used in the induction heating of fluid inside a channel are defined in the literature as flow modifiers and have been shown to significantly increase the heat transfer coefficient [15]. Figure 1 shows two different working principle liquid heater structures.

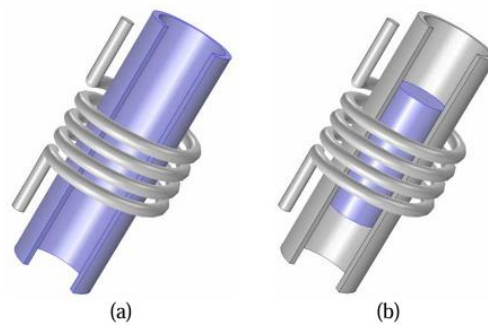


Figure 1. Induction liquid heater models: (a) pool type, (b) floating type [2].

In pool-type induction heaters, generally a single standard heating element (cylindrical pipe) is used, while in floating-type systems, ferromagnetic parts with different geometric shapes can be preferred as the heating element. Although various studies in literature have introduced such floating-type heater geometries, a comprehensive study that jointly examines the historical development, geometric differences, advantages and disadvantages analysis, and intended uses of these apparatuses has not been found. Therefore, the present study aims to guide designers in selecting the appropriate heater geometry, performing magnetic analysis, and evaluating performance processes by examining heater elements with different geometries used in floating-type induction liquid heating systems. Furthermore, these analyses are expected to contribute to the development of new designs.

The effects of the three different insert structures used in this study on heat transfer can be theoretically explained as follows:

#### 1) Floating Profile Insert

- Does not restrict the flow but creates a change in the flow path.
- Increases mixing in regions close to the wall surface.
- Contact with the inner surface of the pipe is longer and more regular.
- The increase in heat transfer may not be as high as with the helical insert

#### 2) Helical / Swirl Insert

- Creates a swirl flow in the fluid.
- Provides an increase in turbulence, but the contact time of the flow with the wall may decrease at high flow rates.
- Therefore, convective heat transfer is higher (also confirmed experimentally) [4].

#### 3) Plain Geometry or Open Channel Insert

- The effect of creating turbulence is limited.
- Flow mostly proceeds axially.

- The heat transfer coefficient is lower compared to the other two geometries.

These evaluations are parallel to similar studies in the literature; in particular, swirl-generating inserts, twisted tapes, and flow guides with variable cross-sections are known to exhibit different performances in heat transfer [5–8].

### 2.4. Calculation of Convective Heat Transfer

In the experimental study, the heat transferred to the fluid was calculated using the convective heat transfer equation:

$$Q = \dot{m}\Delta h \quad (1)$$

$$h = c_p T \quad (2)$$

where  $Q$  is the amount of heat transferred to the fluid,  $\dot{m}$  is the mass flow rate of the fluid,  $\Delta h$  is the fluid enthalpy difference between the outlet and the inlet of the workpiece,  $h$  is the enthalpy of the fluid,  $c_p$  is the specific heat at constant pressure, and  $T$  is the temperature. As the insert geometry changed, the temperature difference changed, and the heat transfer values for each geometry were compared. This approach is an energy analysis method commonly used in induction pipe heating studies in the literature [9, 10].

### 3. Experimental Study

Within the scope of this study, the change in the amount of heat transfer to the water passing through an induction-heated steel pipe, using three different internal geometry inserts, was experimentally investigated. The main goal in the experimental design is to reveal how the convective heat transfer coefficient, which provides the transfer of heat generated on the outer surface of the pipe by induction to the fluid, is modified by the internal geometry. Therefore, the coil, power, frequency, pipe position, and external heating conditions were kept constant in all experiments; only the insert geometry inside the pipe was changed. The boundaries and theoretical framework in the experimental study are as follows:

- The outside of the pipe was heated by induction under constant conditions.
- The only variable parameter was the internal geometry (insert structure).
- The insert geometry:
  - Changes the behavior of the fluid.
  - Improves wall contact.
  - Increases turbulence.
  - Changes the effect of surface area.

Therefore, the heat transfer coefficient and the total heat transfer value differ from geometry to geometry. This theoretical framework forms the basis of the experimental analysis part of the study.

### 3.1. Experimental Test Setup

Induction heating systems are a fast and controlled heating method that generates heat in conductive materials via electromagnetic induction. The photo of the induction machine used in the experimental study is shown in Figure 2.



Figure 2. Figure 2. Induction heating machine (380 Volt, 25 kW).



Figure 3. Experimental test setup.

The pipes used in this study were manufactured from ST-37 steel, as this material has high magnetic permeability, and its induction heating efficiency is proven in the literature [13, 14]. The outside of the pipe was heated under constant conditions with a 25-kW industrial-type induction machine. A closed-loop test setup was established to provide water flow inside the pipe, and the entire system was supported with flow rate, temperature, and pressure control elements.

The test workpiece used in the experiment setup consists of a hollow pipe made of ST37 material with an inner diameter of 25 mm, an outer diameter of 27 mm, a wall thickness of 2 mm, and a length of 150 mm, and 3 different inserts that can fit inside the pipe. Figure 3 shows the experimental setup.

K-type thermocouples with an accuracy of  $\pm 0.1$  °C were used for temperature measurements in the experiments. Water was used as a fluid, and a digital flow meter was used to measure the water flow. The flow rate was kept constant at the desired values

during the experiments, and temperature measurements were carried out.

### 3.2. Inserts Used in the Experiment

The three internal geometries used in the experiment—Helical (Spiral) insert, Square Profile insert, and Neodymium magnet insert—are detailed technically below.

#### 3.2.1 Square profile insert

This insert is a metal profile with a square cross-section and is positioned along the pipe axis. The engineering effects of the profile insert are:

- Partially restricts the flow area inside the pipe, reducing the hydraulic diameter.
- Increases the fluid's contact surface area with the wall.
- Disrupts the boundary layer, increasing turbulence.
- Directs flow lines, causing more energy to be transported to the wall regions.

The dimensions and solid model of the square profile insert used in the experiment are shown in Figure 4.

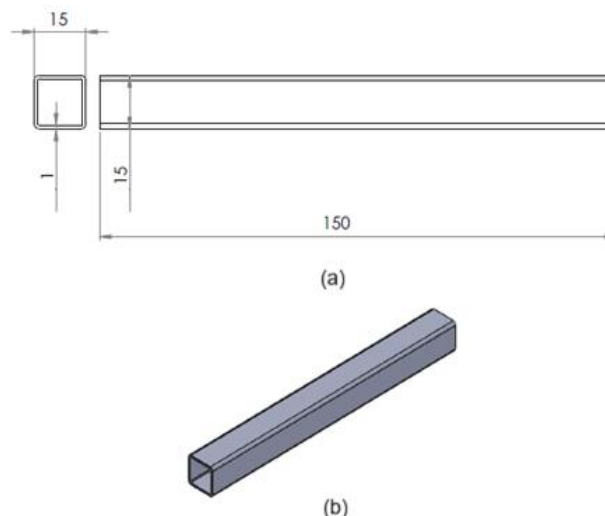


Figure 4. Square profile insert: (a) dimensions, (b) solid model.

#### 3.2.2. Helical (spiral) insert

The helical insert is a structure that creates a swirl flow in the flow. Spiral geometries are commonly used heat-enhancing elements in engineering and create the following effects:

- Transfers flow energy from the central region to the wall.

- Increases micro-mixing by adding an angular velocity component to the axial velocity component.
- However, efficiency may vary due to the collapse or weakening of the swirl flow at high flow rates.

The dimensions and solid model of the helical (spiral) insert used in the experiment are shown in Figure 5.

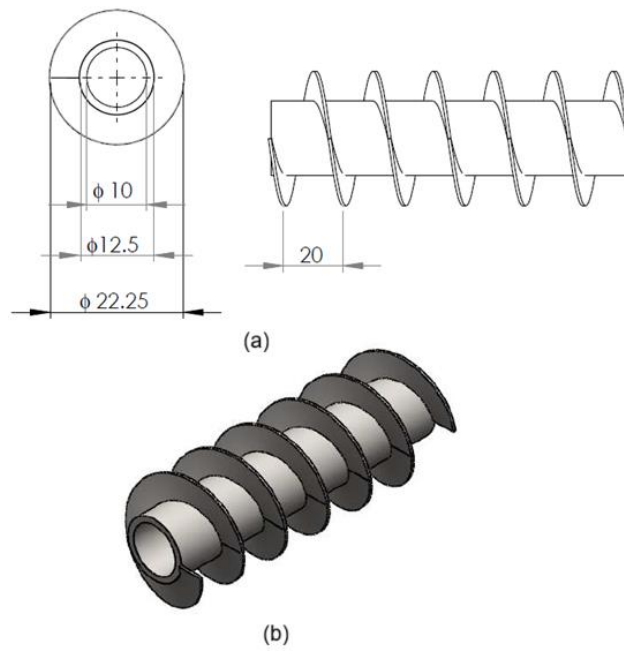


Figure 5. Helical (spiral) insert: (a) dimensions, (b) solid model.

**3.2.3. Neodymium magnet insert**

In this insert, powerful Neodymium magnets are placed inside the pipe with a specific arrangement. The effect of the magnets on the flow is three-fold:

- Local turbulence pockets are formed within the flow.
- Flow lines become irregular and are directed towards the wall region.

- Micro-vortices are formed in the flow region due to the interaction between the metal pipe and the magnet.

The literature states that magnet-based flow guides increase heat transfer, especially at low Reynolds numbers [16]. The dimensions and solid model of the neodymium magnet insert used in the experiment are shown in Figure 6.

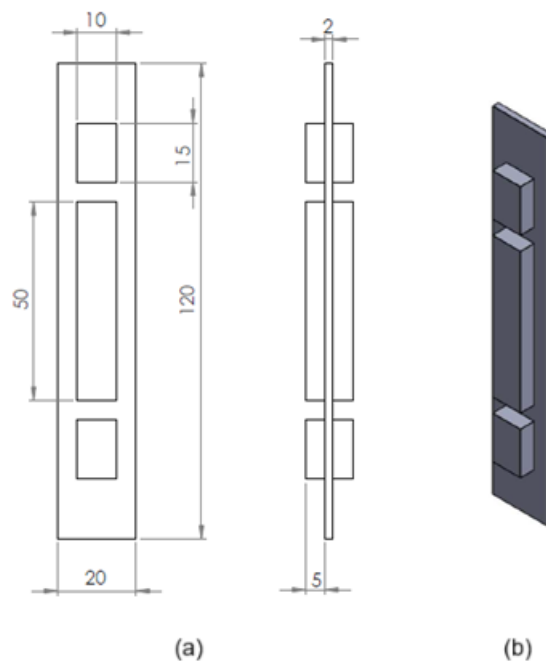


Figure 6. Neodymium magnet insert: (a) dimensions, (b) solid model.

#### 4. Results

A professional industrial induction heating system was employed to heat the steel tube under four experimental conditions: bare tube (no insert), square-profile insert, helical insert, and neodymium-magnet insert. For each case, the inlet and outlet temperatures of flowing water and its volumetric flow rate were measured. The total heat transfer,  $Q$ , from the heated tube to the fluid was then calculated using the energy balance equation. In addition, the voltage and current drawn by the induction machine from the mains were measured. The measured values were used to calculate the three-phase active power,  $P$ , drawn by the induction machine using the following formula:

$$P = \sqrt{3} \cdot V \cdot I \cdot \cos\phi \quad (3)$$

where  $P$  is the three-phase active power,  $V$  is the voltage,  $I$  is the current, and  $\cos\phi$  is the power factor (taken as 0.8).

#### 4.1 Quantitative Evaluation of Experimental Results

The experimental measurements and calculated heat-transfer values for all four configurations—bare tube, square-profile insert, helical insert, and neodymium-magnet insert—are summarized in Table 1. Mass flow rate, temperature rise ( $\Delta T$ ), heat transfer ( $Q$ ), induction-heater electrical power consumption ( $P$ ), and overall ratio ( $Q/P$ ) were comparatively evaluated. The  $Q/P$  ratio represents the fraction of electrical input effectively transferred to the fluid, providing a direct indication of heat-transfer efficiency.

Table 1. Data and calculations obtained from the experimental study

	Insert type			
	No insert	Square profile	Helical	Neodymium magnet
Mass flow rate, $\dot{m}$ (kg/s)	4.87	4.97	4.63	4.65
Inlet-outlet Temperature difference, $\Delta T$ (°C)	6.29	7.50	8.81	8.10
Heat transfer, $Q$ (kW)	2.117	2.581	2.828	2.623
Induction machine power drawn from mains, $P$ (kW)	3.949	3.823	4.007	3.854
Ratio of $Q/P$	0.536	0.675	0.706	0.680

As shown in Table 1, the helical insert achieved the highest heat-transfer rate ( $Q = 2.828$  kW), followed by the neodymium-magnet insert ( $Q = 2.623$  kW) and the square-profile insert ( $Q = 2.581$  kW). The bare pipe resulted in the lowest heat transfer ( $Q = 2.117$  kW). The high amount of heat transfer with the helical insert due to its larger area and the turbulent flow of the fluid is an expected result.

Despite the disadvantages of the Neodymium magnet insert, such as its considerably low surface area and limited allowance for turbulent flow, its use in induction heating systems is based on its high magnetic strength, as Neodymium magnets are known to be the strongest permanent magnets. Thus, Neodymium magnets provide a very high magnetic flux density in the air or in the magnetic core, which increases the heating efficiency by concentrating the magnetic field of the induction coil on the target area. Furthermore, the use of Neodymium magnet inserts minimizes stray currents and unwanted heating around the coil due to the focusing of the magnetic flux onto

the target. With these advantages, it has the second-best heat transfer rate after the helical insert, according to the experimental data and calculations.

The square profile is ranked after the Neodymium magnet insert in terms of heat transfer amount. The bare pipe (no insert) has the lowest amount of heat transfer. Both the lowest surface area and the presence of laminar flow cause the lowest amount of heat transfer.

#### 4.2 Efficiency Analysis via Q/P Ratio

As shown in Table 1, the comparison of heat transfer relative to electrical input power ( $Q/P$ ) revealed that the helical insert also yielded the highest energy efficiency ( $Q/P = 0.706$ ). This improvement is attributed to the ability of the helical geometry to enhance boundary-layer disruption and increase surface exposure under swirl-induced convection. The neodymium-magnet insert followed closely ( $Q/P = 0.680$ ), benefiting from intensified magnetic flux

localization and micro-scale vortex generation. The square-profile insert also demonstrated a considerable improvement over the bare pipe ( $Q/P = 0.675$ ), primarily due to increased surface contact and hydraulic constriction. The bare tube exhibited the lowest efficiency ( $Q/P = 0.536$ ) because of minimal turbulence, large laminar boundary-layer thicknesses, and a relatively low fluid–surface interaction area. These findings collectively validate the effectiveness of using inserts to enhance convective heat transfer in induction-based heating systems.

## 5. Conclusions

In this study, the extent to which water passing through an induction-heated steel pipe is heated using different internal geometric insert structures was experimentally investigated. Four different experimental conditions were evaluated: bare pipe (no insert), square profile insert, helical (spiral) insert, and neodymium magnet insert configurations. The findings and energy analyses are summarized below:

- The helical (spiral) insert provided the highest heat transfer among all configurations. The helical

(spiral) insert's ability to disrupt the boundary layer, increase wall contact, and guide the flow supports this performance.

- The neodymium magnet insert was found to have the second-highest heat transfer rate after the helical (spiral) insert, due to the magnetic flux focusing on the target and the minimization of stray currents and unwanted heating around the coil.
- The bare pipe (no insert) has the lowest amount of heat transfer. Both the lowest surface area and the presence of laminar flow cause the lowest amount of heat transfer.

This situation confirms that the inserts are effective in increasing heat transfer. The results obtained are consistent with the findings in the literature that the use of inserts increases the convective heat transfer coefficient.

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