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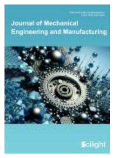

Article

Development of an Injection Nozzle Heating System to Produce Automotive Control Cables

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Abstract: The automotive industry plays a vital role in the global economy, significantly contributing through job creation, resource utilization, and driving technical and technological advancements. Control cables play an indispensable role in various vehicle mechanisms, including the control of windows, doors, and critical functions such as the handbrake and throttle. The terminals attached to these control cables are small, die-cast components, most commonly fabricated from light alloys with low melting temperatures, such as the zinc-based alloy Zamak. One of the key challenges encountered in the production of these terminals is the difficulty in maintaining consistent heating of the injection nozzle, which can hinder the smooth removal of parts from the mold. This research proposes an innovative method to improve the heating of injection nozzles used in the manufacturing of zamak control cable terminals by employing electromagnetic induction. Typically, the heating process is conducted using electrical resistors, which lack precision in temperature regulation and respond slowly to fluctuations in nozzle temperature. The solution introduced in this study involves an induction heating system, tuned to operate at 155 kHz and 410 W of power. The system's design features a multi-coil solenoid inductor, optimal for cylindrical components, and incorporates a pyrometer for continuous temperature monitoring. Finite Element Method (FEM) analysis revealed that maintaining an injection nozzle temperature of 550 °C requires the surrounding injection set to reach 600 °C. The return on investment for implementing this induction heating technology was calculated to be around 7 years and 8 months.

Keywords: automotive industry; control cable assembly; die casting; electromagnetic induction

1. Introduction

The automotive industry plays a vital role in the global economy, significantly contributing through job creation and resource utilization, while it drives many technical and technological advancements. Linked to the automotive sector is the automotive components industry, tasked with producing a diverse range of components essential for car construction, including items like control cables. Control cables are essential components in automotive systems, enabling key functions such as the movement of windows and doors, as well as the operation of systems like the handbrake and throttle. Their assembly involves several stages, which include the production of various integral parts [1]. The cable terminals are usually produced through die-casting using lightweight alloys with low melting points, primarily Zamak—a zinc-based alloy. However, maintaining consistent temperature control during the injection molding process can be problematic. This often leads to difficulties in successfully removing the terminals from the mold [2]. The heating techniques applied in the automotive sector significantly vary, depending on the method of heat transfer and the specifics of the process. In more severe cases, the reported difficulties can result in equipment downtime. Since its inception, there has always been a need for heating in the automotive industry, due to the manufacture of metallic materials, whether in casting, welding, plastic forming, or other processes. The manufacture of polymers also involves heating to temperatures that allow them to be malleable [3]. Their use has increased over the years due to their durability, low weight, and easy processing [4]. Despite the common goal of providing energy in the form of heat, heating processes in the automotive industry greatly differ in their heat transfer principle, the equipment used, the complexity of the process, and other characteristics that enable heating. These processes depend on a series of factors, such as necessity of heating an isolated component or raw materials, requirement for total or localized heating of a component, quantity of material to be heated and energy efficiency, temperature to be reached and heating speed, and capital available for purchasing, operating, and maintaining the heating system [5]. Consequently, and considering the specifications and technical needs of each process, various heating techniques have been developed, so that there is no ideal heating process for all possible applications. Gas heating systems rely on a pressurized reservoir containing flammable fluids such as natural gas, propane, or butane. The gas is transported to the heating site, where it is ignited to produce a steady flame [6]. Laser beam heating directs a highly concentrated electromagnetic radiation beam onto a workpiece, raising its surface temperature [6]. Although less suitable to heat large areas, laser beam heating is invaluable for cutting and welding operations in the automotive industry [3]. Electron beam heating involves firing a high-velocity beam of electrons at a target area, resulting in rapid and localized heating [6]. Electrical resistance heating works by passing an electric current through a high resistance metallic conductor, and is used in vehicle body assembly lines where sheets and panels are joined [6]. Electromagnetic induction heating works by inducing an electric current within the material to be heated without direct contact, unlike direct electrical resistance heating. The induced current generates heat through the Joule effect [7]. This method is versatile and is widely applied in the automotive industry.

One notable application of induction heating was developed by Hornby et al. [8], who designed a system to heat fuel injectors using induction. In their design, a central tube is heated by induction, which in turn raises the temperature of the fuel passing through it before injection into the combustion chamber. This approach reduces emissions during vehicle startup by eliminating the need for wiring in the fuel system and preheating the fuel for better combustion efficiency. Sun et al. [9] explored the impact of high-frequency induction heating parameters on the heat transfer efficiency and heated area of workpieces using an electromagnetic-thermal FEM simulation. Their findings indicated that an increased magnetic flux significantly expanded the heated area and raised the maximum temperature. Moreover, the authors discovered that the spacing between the inductor and workpiece plays a crucial role in heating efficiency. Increasing the gap from 1 to 3 mm caused an 81% drop in maximum temperature and reduced the heated area, lowering the amount of heat transferred to the component. While frequency variations between 180–250 kHz had minimal effect on the heated area, the increase in maximum temperature was substantially lower compared to increases in magnetic flux. Guerrier et al. [10] applied an induction heating system to improve mould heating for the injection moulding of acrylonitrile butadiene styrene (ABS) and high-density polycarbonate (PC) polymers. The authors developed a numerical model using the Ansys® software, incorporating a high-speed camera system to observe mould filling, which occurred in about 400 ms. The induction heating raised the mould temperature to 110–200 °C for ABS and 255–250 °C for PC, significantly improving mould cavity filling and eliminating common injection issues. This modification also led to enhanced surface quality and prevented solidification problems in thicker sections of the mould, ensuring complete part formation. Yang et al. [11] investigated the thermal characteristics of induction heating in the injection process during two-phase zone continuous casting (TZCC) of high-strength aluminium alloys. A 3D TZCC model was developed to analyse the temperature field, focusing on the influence of a stepped diameter mould and controlled temperature. Numerical and experimental results demonstrated that the groove in the mould enhances magnetic field uniformity, while the convex plate strengthens electromagnetic coupling, improving the vertical temperature gradient in the mushy zone. Optimizing mould structure and temperature (783–823 K) enabled the production of 2D12 aluminium alloy bars with superior surface quality and elongation of 16.2%. Yang et al. [12] explored the role of induction heating in the two-phase zone continuous casting (TZCC) process for producing 2D12 aluminium alloy tubes. A 3D TZCC model was developed to analyse electromagnetic-thermal coupling and fluid flow behaviours under various mould temperatures. The heat flux from the induction-heated mould creates a convex isothermal line at the dendrite coherency point and circular thermal convection ahead of the mushy zone. Results showed that increasing mould temperatures significantly enhance transverse flow velocity while maintaining constant upward flow at the outer wall. Optimized induction heating contributed to improved thermal uniformity and reduced solute segregation during tube casting. Thongsri et al. [13] presented the development of a high-efficiency small induction furnace (SIF) for glass souvenir production, integrating induction heating with multiphysics analysis. The SIF, comprising copper coils, a ceramic jig, and a graphite crucible, was optimized using electromagnetic and thermal analyses. Results demonstrated that a ferrite flux concentrator significantly enhanced magnetic flux density (B) by 159% at 1000 W, improving heating efficiency. The power applied to the coils directly increased B, with the flux concentrator focusing the magnetic field more effectively. The developed SIF achieved superior thermal performance, supporting cleaner and more efficient glass melting in practical applications. Despite its significant advantages, the application of induction heating in injection processes faces unresolved challenges that limit its industrial adoption. Current research often fails to address the precise and real-time control of nozzle temperature, which is critical to preventing material solidification and ensuring consistent product quality. Moreover, the high operational temperatures required by these systems frequently degrade the nitrided layer on the injection nozzle, leading to premature wear, increased maintenance requirements, and operational downtime. Limited attention has also been given to the economic feasibility of advanced heating technologies.

This research proposes an innovative method to improve the heating of injection nozzles used in the manufacturing of Zamak control cable terminals in a given industrial company by employing electromagnetic induction. Typically, the heating process in the production lines is currently conducted using electrical resistors, which lack precision in temperature regulation and respond slowly to fluctuations in nozzle temperature. The solution introduced in this study involves an induction heating system. The system's design features a multi-coil solenoid inductor, optimized for cylindrical components, and incorporates a pyrometer for continuous temperature monitoring. To ensure the nozzle reaches a consistent temperature of 550 °C, a FEM analysis is conducted to estimate the temperature required across the injection assembly. This simulation helps determine the optimal thermal conditions needed for efficient operation. The study concludes with an analysis of the return on investment, evaluating the system's cost-effectiveness based on the heating performance and associated benefits.

2. Methods

2.1. Adopted Methodology

This study utilized the Design Science Research (DSR) methodology, which is distinguished by its emphasis on creating innovative concepts, systems, or solutions, grounded in theoretical knowledge and validated through practical application [14]. The DSR process typically follows six key stages:

- Problem Identification: This initial stage involves analyzing existing equipment, systems, or processes to identify operational issues, limitations, or areas for improvement. Additionally, it may be driven by emerging technologies or methodologies that present more advantageous alternatives.
- Objective Definition: Based on the identified problems, this phase sets clear goals and solutions, including considerations such as the required technology, spatial needs, and delivery timelines.
- Design and Development: At this stage, the envisioned solutions are developed, taking theoretical models and translating them into practical designs.
- Demonstration: The designed solution is then implemented within the relevant equipment, system, or process to test its functionality in real-world conditions.
- Evaluation: Following the demonstration, the solution is critically assessed to determine whether the identified problems have been effectively resolved. Additionally, any unexpected quantitative or qualitative results are analyzed, with hypotheses developed to explain deviations.
- Conclusion: This final phase compares the initial situation with the outcomes achieved after implementation. It also involves documenting the knowledge gained throughout the process and identifying validated solutions or anomalies that may require further investigation, possibly inspiring future work.

The outlined steps are not strictly linear; new information can arise at any stage, prompting revisions or iterations of earlier phases. Even upon completion, conclusions drawn from the process may lead to alternative solutions. This flexible methodology supports the enhancement of existing systems and processes while contributing to the generation of new technical knowledge. In this study, the DSR framework was chosen because this study aimed to develop an innovative heating method based on induction heating, guided by iterative design, analysis, and numerical evaluation. The application of the DSR methodology begins in the next two subsections, Sections 2.3 and 2.4, with Step 1—Problem Identification. In this step, the control cable and different components are characterized, the manufacturing process is described and divided into smaller sub-processes. The existing problems are identified. In Step 2—Objective Definition (Section 2.5), the main objective of the work is quantified, and the requirements and constrains defined, arising from the operational characteristics required for the system. Step 3—Design and Development is presented in Section 3.1. This step consists of the pre-design, in which the plausible solutions are compared, and a final choice is made on the type of heating system should be developed in the further steps. Steps 4 and 5—Demonstration and Evaluation correspond to the entire Section 3.2, related to the design process. In these steps, the proposed concept is described, and both analytical and numerical verifications carried out. Evaluation in particular also includes the cost analysis and return on investment calculated, so that the deciding actors can evaluate the feasibility of physically validating/implementing the proposed system in a real scenario. Finally, Step 6—Conclusion, the last stage of the DSR methodology, is presented in Section 4, addressing how the proposed system contributes to the field and future work involving experimental validation.

2.2. Financial Approach to Cost and Return on Investment

The economic feasibility of implementing the induction heating system was evaluated through a return on investment analysis, considering both the total implementation cost and the expected annual savings. The cost of integrating the induction heating system into the existing production infrastructure includes:

- The purchase of induction heating equipment (generator, inductor, and control system);
- Installation and adaptation costs for 60 Zamak injection machines.

The financial benefits of switching to induction heating were estimated by analyzing the reductions in:

- Component Replacement Costs: The elimination of excessive wear on electric resistors and injection nozzles, leading to reduced maintenance expenses;
- Production Downtime: Fewer machine stoppages due to nozzle blockages and component failures, improving manufacturing efficiency;
- Energy Consumption: The higher efficiency of induction heating compared to conventional resistive heating.

The payback period, which represents the time required to recover the initial investment through cost savings, is calculated as:

$$\text{Payback period} = \frac{\text{Total implementation cost}}{\text{Annual savings}}$$

Future studies could incorporate experimental validation of energy consumption reductions and a detailed sensitivity analysis to assess variations in cost-effectiveness under different operational conditions.

2.3. Fabrication Process of Control Cables

A control cable consists of various components designed to transmit mechanical movement between its two ends, as illustrated in Figure 1. The core structure of a control cable includes a metal cable, which is encased in an inner coating, followed by a spiral layer, and then an outer coating. The terminals, located at the ends of the metal cable, enable it to execute its intended actuation function. These cables are used in several key operations, such as engaging the handbrake, accelerator, ignition, or clutch, as well as opening doors, windows, the boot, or the fuel cap. The metal cable is formed by helically twisting thin metal filaments together. The number of filaments used depends on the function of the cable, and increasing the number gives the element greater capacity to transfer stress. The cable ends undergo plastic deformation to create a mushroom-shaped head, which is an organized grouping of filaments that enhances the connection of the cable to the terminal. The inner lining prevents direct contact between the metal cable and the spiral, to prevent wear and tear, and is a polymeric material obtained by extrusion. The spiral, typically made of steel, is a metal component created through a rolling process. It provides increased strength and stiffness to the mechanism. The outer tube serves to protect these internal elements and minimize any noise generated by their movement. It is made by extruding polyvinyl chloride (PVC) or low-density polyethylene (LDPE). All these components are secured within the vehicle using spiral terminals, of which there are always at least two for each control cable, obtained by injection moulding. The cable ends are fitted with terminals, which are produced through a sequential die-casting process using Zamak, a zinc-aluminium alloy. The first step involves injecting the material onto the mushroom-shaped end of the metal cable. Next, additional components are integrated on various assembly lines, before a final injection is applied to create the last terminal [15].

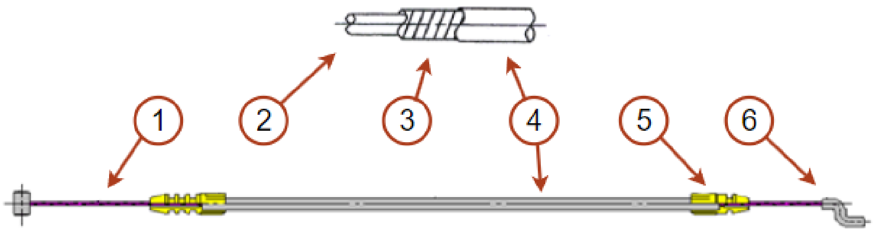

Figure 1. Components of a control cable: metal wire (1), inner coating (2), spiral (3), outer coating (4), spiral terminal (5), and control cable terminal (6).

As illustrated in Figure 2, the manufacturing process of control cables consists of various operations that are mainly grouped into two phases: component production and assembly. While these phases are categorized separately, these are interconnected throughout the production process. A key example is the injection of Zamak terminals; the first terminal is usually injected onto the metal wire, while the second terminal, which is the final major component added to the control cable, is previously fabricated and mounted in the metal wire loose end, or injected into it. In this scenario, a production task is integrated into the assembly process.

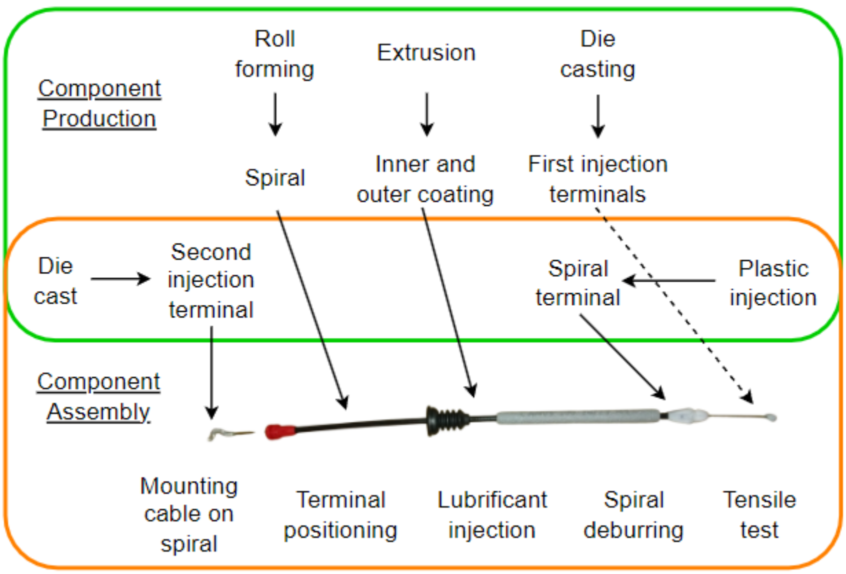

Figure 2. Diagram illustrating the construction process of a control cable, as well as the different stages and main tasks carried out.

2.4. Problem Description

During the production of the control cable, the nozzle is heated by a system that uses an electrical resistance, with weaknesses such as: low temperature which does not heat the top of the nozzle up to the desired point, operating at top capacity, excessive temperature in the nozzle body, slow energy transfer method (which allows the temperature at the top of the nozzle to drop significantly when it is exposed to air or touches the injection die, leading to the unwanted solidification of the zamak in the injection nozzle, blocking it), and absence of nozzle temperature control. The electrical resistance reaches 620 °C, which allows the heating of the nozzle tip up to 550 °C. Thus, to achieve the desired temperature at the top of the nozzle, and to avoid the Zamak's solidification in the nozzle, the nozzle is overheated, which in turn removes the nozzles' nitrided layer. This component is subjected to a nitriding heat treatment, since it creates a hardened thin layer in the component, with high resistance to abrasion, wear, and chemical attack by the molten aluminium. Since this treatment is performed at a temperature between 550 and 580 °C, being exposed to similar or higher temperatures will be detrimental to the nitrided layer, which will start to lose its properties. Consequently, the 620 °C heating of the injection nozzle by the electric resistance will destroy the hardened layer of the nozzle, and reduce its chemical and mechanical resistance, which leads to a faster deterioration of the component, requiring it to be replaced with a new one ahead of schedule.

2.5. Requirements and Constraints

In this work, the main objective is to find and develop a heating system capable of guaranteeing the heating of the injection nozzle and tip in such a way that the Zamak does not solidify in them or in the sprue of the injection mold, i.e., the previously mentioned problems resulting from insufficient heating. The heating system also needs to guarantee a temperature of 550 °C at the top of the nozzle. This system must reach the required temperature with a rapid response (at least 100 °C/min) to the cooling that occurs during the injection cycle (derived from the distance between the structure and the injection nozzle, an operation during which these components are exposed to convection phenomena with the relatively cold air). Thus, a requirement associated with this system is a high energy heating rate, specified in Section 3.1.5. It is also necessary to control the temperature in the injection nozzle and tip, a function that the current system does not provide, by measuring and responding to the heating system whenever this value is outside the pre-set parameters. Another requirement, of lesser importance, is to change the current system to a more durable one with less need for maintenance. Currently, the injection nozzle and tip have a service life of approximately three and one months, respectively. It is required to double these values.

The limitations imposed on the new heating solution can be summarized as difficulties in experimental validation, cost and available space. Experimental validation, which would significantly increase the robustness of this study, was not possible to accomplish due to unavailability of equipment during the study and authorization from the company to modify the production line. However, the FEM is an established method, and preliminary studies and convergence analyses were carried out in the background to support the presented results. Cost is a known issue with induction heating systems, and a cost analysis is performed to assess the viability of the proposed system. The available space, shown in green in Figure 3, is very small and consists of the volume currently occupied by the electric heating element and the protective cup. Since there is a risk of this area being hit by Zamak projections, the protection must be maintained.

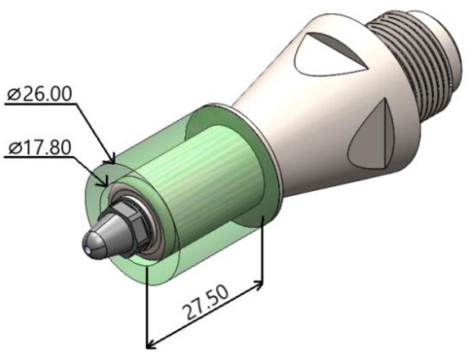

Figure 3. Space available to heat the tip and nozzle.

3. Results

3.1. Preliminary Solutions

Pre-design involves analyzing the heating methods employed in the industry and closely observing the injection process on the existing machine to gain a comprehensive understanding of all related factors. All the previously described heating techniques are discussed, focusing on their advantages, disadvantages, applicability, and the possibility of solving the existing problem, with the aim of determining which of these techniques are viable options for this work.

3.1.1. Electrical Resistance

This is the currently utilized method to heat the nozzles and tips in the company's control cable terminal injection machines (Figure 4). The equipment is cost-effective and straightforward to maintain or replace in case of failure. However, temperature control relies on setting a specific temperature range, managed by turning the heating element on or off, without direct measurement of the temperature at components like the nozzle and injection tip. Because the shape of the heating element can be adapted to the geometry of the body to be heated, uniform heating of the body is guaranteed. However, since heat is transferred by conduction, initially between the heating element and the nozzle, and then between the nozzle and the nozzle, a slow response to the cooling of the top of the nozzle is achieved. This phenomenon is still difficult to control, as there is no way of measuring the temperature of these components.

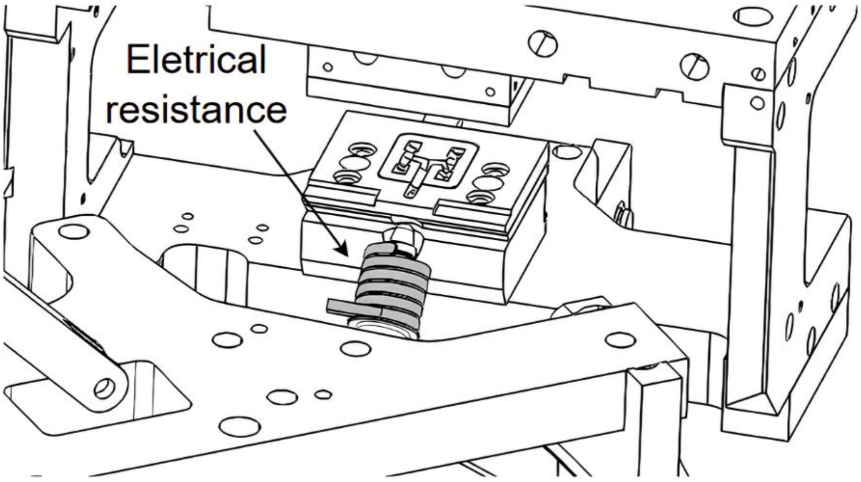

Figure 4. Sketch of electric resistance heating.

3.1.2. Gas Heating

Gas heating offers a continuous flame, ensuring a steady heat supply that helps maintain the temperature in the nozzle. However, it is highly susceptible to air currents that can deflect the flame away from the nozzle. Additionally, gas heating poses safety risks, particularly concerning potential gas leaks. The initial sketch of this option (Figure 5) uses a ring around the nozzle, with the appropriate holes to project the flame towards the nozzle. This arrangement would minimize the effect of wind on the flame. However, heating the nozzle with gas is a relatively dangerous process due to the possibility of gas leaks. Adopting this heating method would necessitate acquiring a sophisticated gas heating system and obtaining the necessary certifications, resulting in a substantial initial investment.

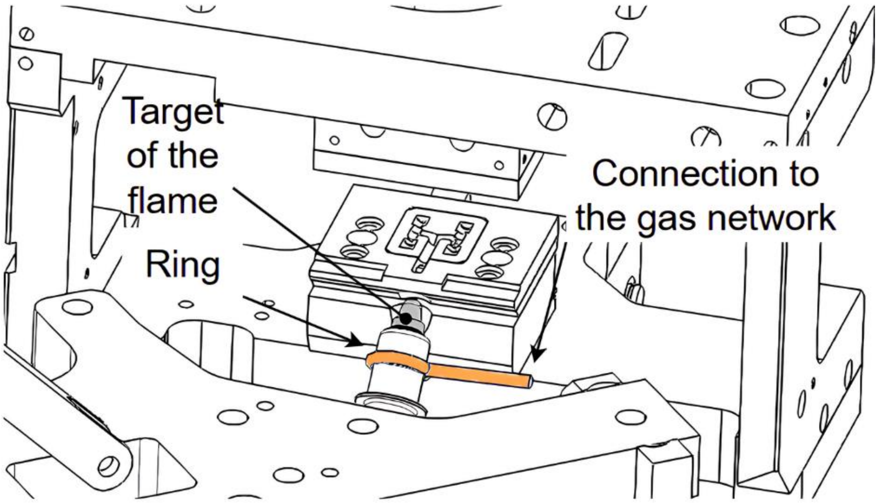

Figure 5. Sketch of the gas heater.

3.1.3. Laser Beam and Electron Beam

The two heating methods provide excellent process control, particularly in terms of the quick response to cooling the nozzle, due to the high rate of energy transfer inherent in the processes, and the preservation of the desired temperature in the component to be heated. Due to the operation of these heating techniques, the laser or electron beam emitter would need to be positioned to aim at the nozzle, supported by a fixture that directs the electromagnetic or electron radiation beam towards it (Figure 6). However, the heating of the nozzle and nozzle tip would be focused on the face of incidence, and not around these components, which would result in insufficient heating in the area not hit by the beam.

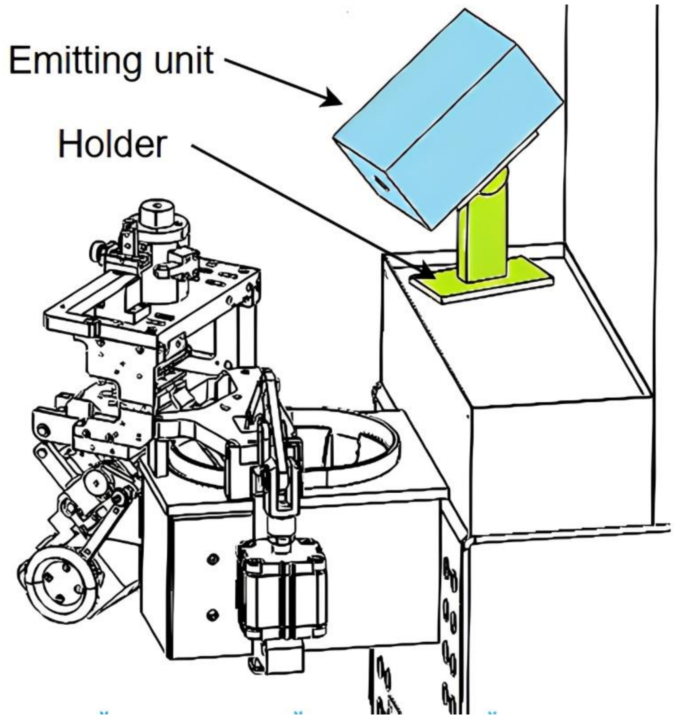

Figure 6. Sketch of laser and electron beam heating.

3.1.4. Electromagnetic Induction

The implementation of an electromagnetic induction heating system can be applied to each nozzle individually. Thus, there is no need for a general system, as with gas heating. As a result of its operation, the nozzle and injection tip can achieve uniform heating through an inductor installed around them, similar to the existing electrical resistance heating method, as opposed to laser and electron beam heating, which focuses the heating of the component on the incidence face. The inductor is linked to an external circuit that is directly connected to both the generator and the cooling system, as illustrated in Figure 7.

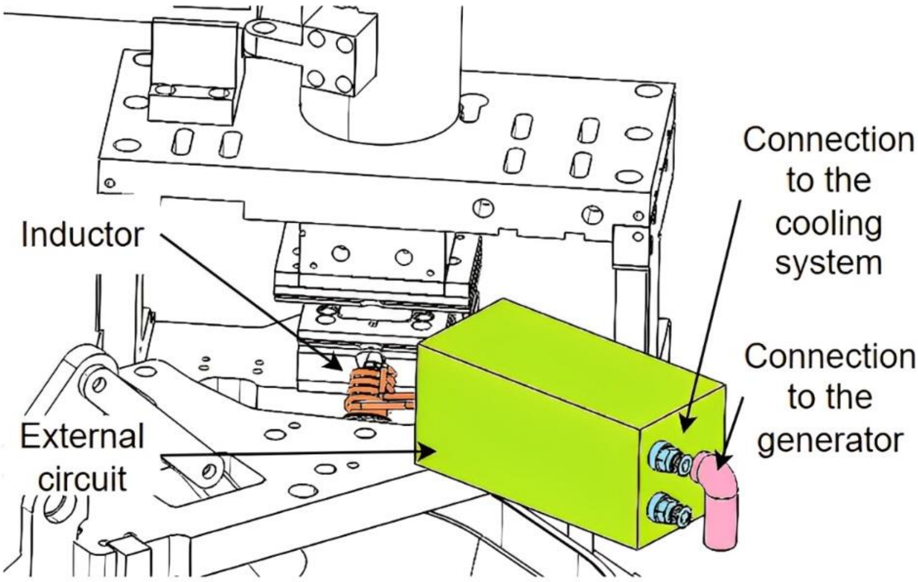

Figure 7. Sketch of electromagnetic induction heating.

This system offers several advantages, including straightforward automation of the heating process, continuous monitoring of the workpiece temperature, and a quick response to nozzle cooling due to its rapid heating capabilities. This system is also safer, less polluting and more energy efficient when compared to the gas and electrical resistance heating. However, it comes with a high cost and requires a thorough analysis for its implementation to optimize its performance.

3.1.5. Final Selection

Thus, among the heating techniques examined, electromagnetic induction emerges as the most viable solution to address the issue of heating the injection nozzle and tip. The advantages of utilizing an electromagnetic induction system include: rapid heating of the injection nozzle through direct heat transfer by induction, precise temperature control via a pyrometer (enabling the system to adjust based on the measured temperature), and enhanced energy efficiency. This system has an average heating rate of 500 °C/min, which satisfies the required the heating response defined by the company.

3.2. Design

3.2.1. Proposed Solution

The induction heating system applied to the machine is shown in Figure 8. The injection nozzle heating system by electromagnetic induction generates an electric current through a generator (a). An external circuit (b) is also used to convey the electric current, with 410 W of power and a frequency of 155 kHz, to the inductor. By using a pyrometer (c), the temperature at the top of the injection nozzle can be measured and evaluated by the control unit (d). These components are placed near the injection zone, on the support table (e), while the chiller (f), which is responsible for cooling the water travelling through the system, is located at the bottom of the machine.

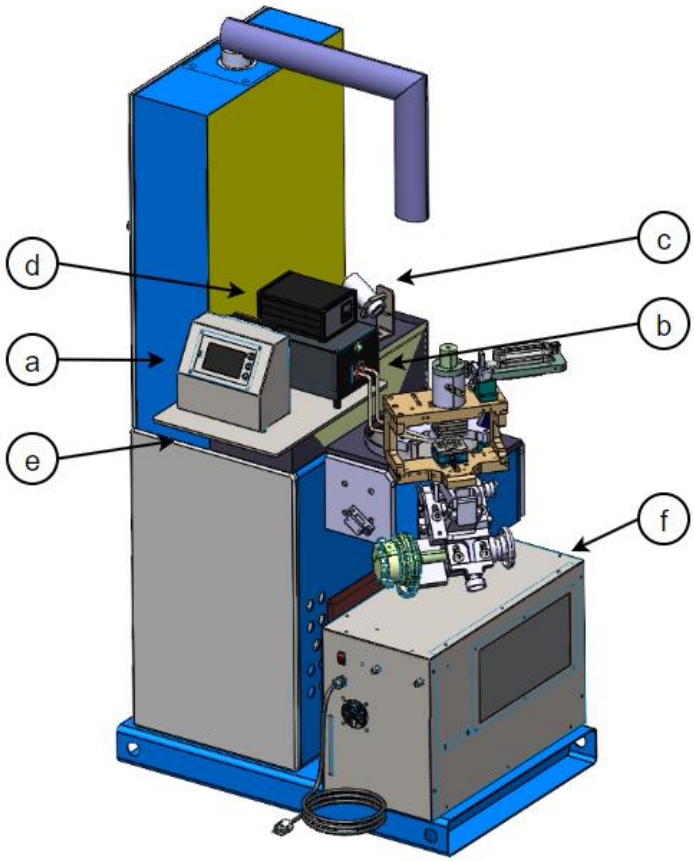

Figure 8. Injection machine with the applied induction heating system.

The inductor is the component directly responsible for heating the desired workpiece, by generating an electromagnetic field through the electric current that runs through it [16]. This field induces an electric current in the metal workpiece that causes it to heat up due to the Joule effect: due to the high resistivity (opposition offered by a material to the passage of electric current) of the metal material, the passage of current causes the metal body to heat up [17,18]. Since the work piece has a cylindrical shape, the inductor has a multi-spiral helical coil configuration, shown in Figure 9, as this configuration maximises the heating of this geometry [19]. This coil is crossed by chilled water, which prevents its degradation through exposure to the heat emitted by the workpiece. The inductor is protected by the cup, as was the case with the old electric resistor, which protects it from any Zamak projections. The pyrometer is capable of measuring temperatures between 100 and 2000 °C through the infra-red radiation emitted by the workpiece, without the need to physically contact it. The adjustable bracket on which the pyrometer is mounted allows it to be aligned with the top of the injection nozzle, while the focus distance can be adjusted directly on the pyrometer.

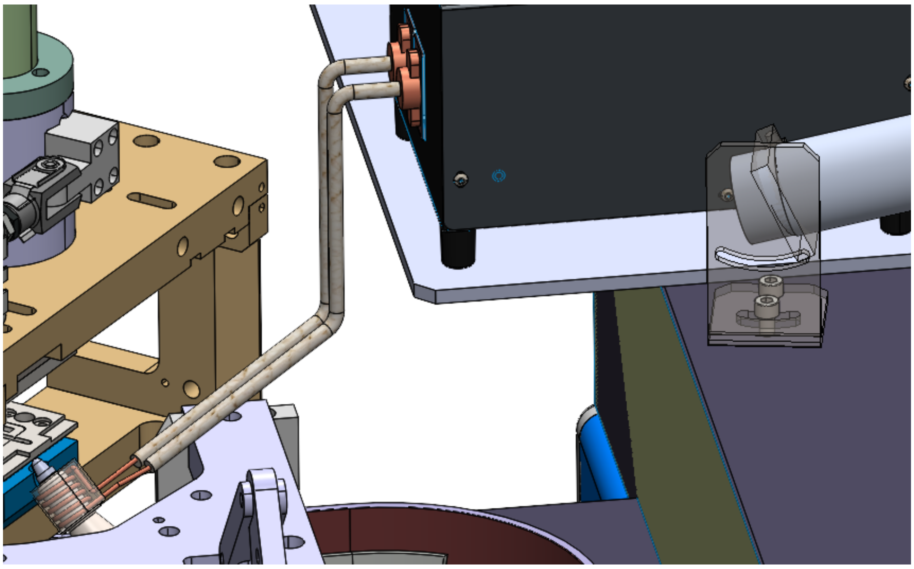

Figure 9. Coil and protective cup installed on the injection nozzle.

3.2.2. Materials

Both the nozzle and the injection nozzle are lathing components made from AISI H13 steel, a steel suitable for hot work that is highly resistant to wear and high temperatures. It is commonly used in applications such as aluminium and plastic casting moulds, as well as various machine components [20]. The inductor is made of copper, which is the most suitable material for this application as it has excellent electrical conductivity, low cost, good malleability, and high corrosion resistance. It is a metal that is readily available for general sale, at low cost, and in various geometries, mainly tubes and wires [21]. For the support table and adjustable support, AISI 1045 (C45E) steel was selected. This is a frequently used material for general mechanical construction due to its good mechanical properties at a low cost, good machinability and the possibility of applying various treatments. In this case, the components will be galvanised, a process that provides a zinc film to prevent corrosion due to contact between the components and atmospheric air, as well as possible zamak projections [22].

3.2.3. Component Selection and Verification

To dimension the components of the inductive system, it is first necessary to determine how much heat must be generated, and transferred to the top of the injection nozzle, to reach and maintain a temperature of 550 °C. This step was carried out by a FEM simulation, which is a complex numerical tool that allows the resolution of various problems whose solution is extremely difficult, or even impossible, to obtain analytically [23]. Using the FEM, a thermal analysis was carried out, which considered the injection tip and nozzle with their respective material associated, from the Solidworks Student Edition® (Dassault Systèmes, Vélizy-Villacoublay, France) material library, as well as the respective contacts and mesh. In this analysis, the cylindrical volume represents the part of the injection nozzle subjected to induction heating (coloured in Figure 10a). The thermal conductivity of the materials is 27 W/(m·k) [24]. This volume that is affected by the electromagnetic field, generated by the inductor, was determined and defined as the heat generation zone, and is axially limited by the cylindrical section of the tip, and radially by the depth of 4.65 mm, which is the maximum depth before reaching the thread that locks the nozzle in the tip, and was selected to maximize the heat generation zone in the tip. Convection due to contact with atmospheric air at a temperature of 20 °C (293.15 K) was also considered with a convection coefficient of 25 W/(m^2·k) [25] (Figure 10b). Figure 10c provides the quadratic tetrahedrons mesh overview and respective details, including the blended curvature-based mesh strategy, the element sizes (minimum and maximum), and the total number of elements. Relatively to the solver settings, the FFEPlus was used. Formerly to the choice of these mesh settings, a mesh convergence analysis was carried out by comparing different size meshes, aiming to ensure that the output temperatures became independent on the mesh size, leading to the reported mesh characteristics. As shown in the simulation results of Figure 11, the conduction of heat occurs from the heat generation zone (highest temperature zone: 600 °C) to the top of the injection nozzle (coldest zone: ≈550 °C), through the components, during which the temperature is gradually reduced. This effect is most noticeable at the top of the injection nozzle, due to exposure to relatively cold atmospheric air, which is the main method by which the component is cooled.

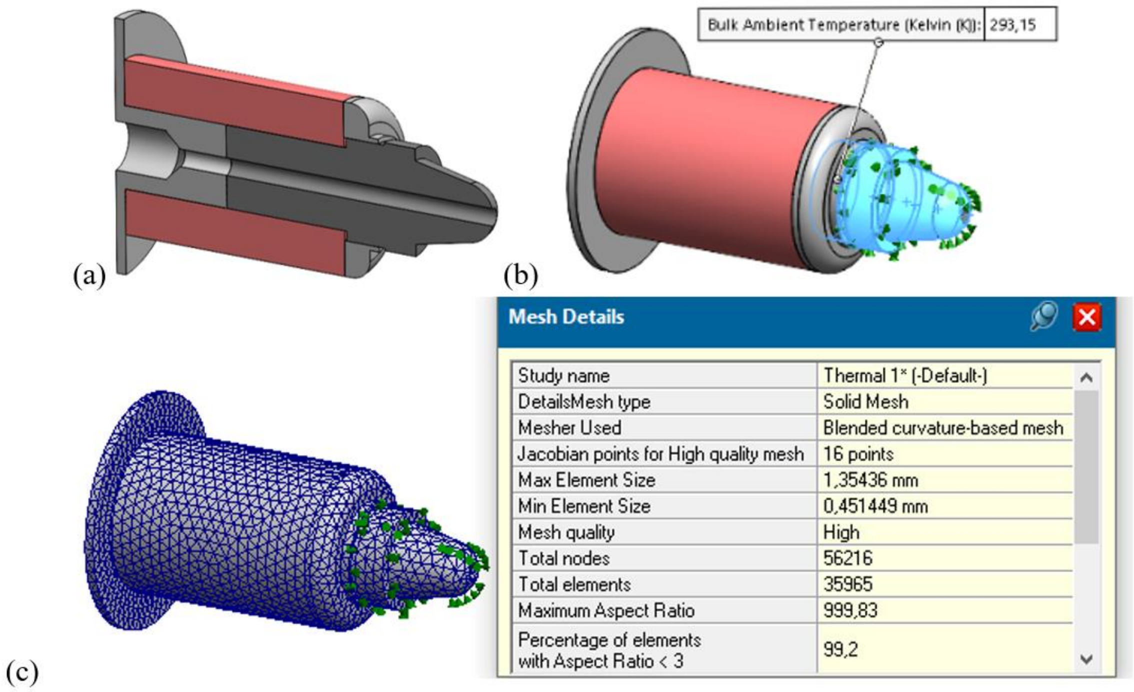

Figure 10. Thermal analysis of the injection nozzle and tip: (**a**) heat generation zone; (**b**) definition of the convective heat transfer; (**c**) mesh details.

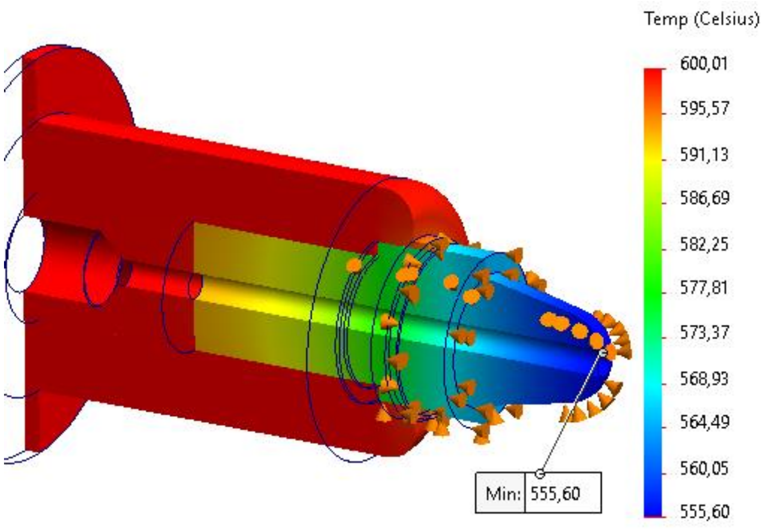

Figure 11. Temperature distribution in the injection nozzle and tip.

As mentioned before, the solenoid-shaped inductor creates the most efficient heating pattern in cylindrical workpieces, therefore is the most appropriate geometry for this application [19]. Its design also focused on occupying the space available inside the protective cup (presented in Figure 3) and presenting the higher number of turns as possible, since this parameter increases the inductor's efficiency [24]. As a result, the designed inductor (Figure 12) is characterized by being made up of five turns obtained by winding a copper tube (inner and outer diameters of 1.50 and 2.50 mm, respectively) to generate an inner diameter of 21 mm. The diameter and thickness of the copper tube were selected by consulting available pipe sizes for general sale, and simulating the 3D model so that it fits inside the protective cup.

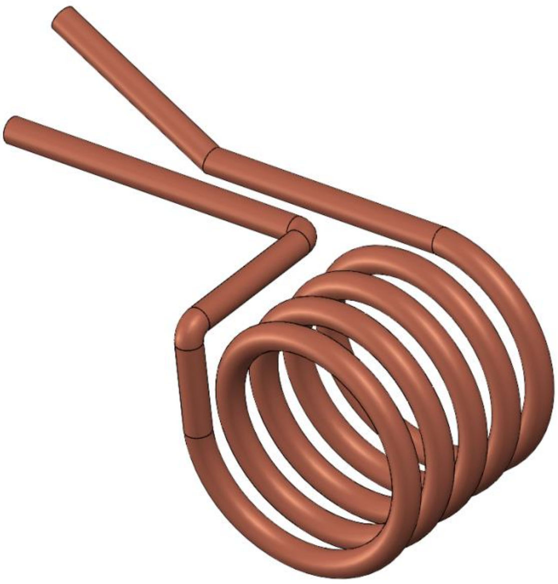

Figure 12. Proposal for injection nozzle heating inductor.

The main characteristics to select a generator for this application are frequency and power, which will be determined next for heating the injection nozzle. The frequency of the electric current generated is determined by the following equation, which defines the penetration depth of an electromagnetic wave in a given material [24]

$$\delta = \sqrt{\frac{1}{\pi f \sigma \mu}} \Leftrightarrow f = \frac{1}{\pi \delta^2 \sigma \mu}$$

Below is a description of the variables that make up this equation:

- Depth of penetration (δ): 4.65×10^{-3} m;
- Electrical conductivity of the workpiece (σ): 5.60×10^{3} S/m. The workpiece corresponds to the component heated directly by electromagnetic induction, namely the injection nozzle, which is made from MG50 steel [26];
- Magnetic permeability (m): 1.69×10^{-5} H/m. This value is determined by $m = B/H$, where the magnetic field (B) is calculated through the equation presented below [24], and the field intensity (H) is determined by the equation $H = (2\pi r)^{-1}$ [27]. The procedure used consisted of determining the magnetic field:

$$B = \frac{n \times \mu_o \times I}{l_s} \times \cos(\theta) = \frac{5 \times 4\pi \times 10^{-7} \times 1.56}{2.45 \times 10^{-2}} \times \cos(0) = 4.01 \times 10^{-4} \text{ T.}$$

- Number of solenoid turns (n): 5;
- Magnetic permeability in vacuum (μ_o): $4\pi \times 10^{-7}$ H/m [24];
- Length of the solenoid (l_s): 2.45×10^{-2} m;
- Angle of inclination between the magnetic field and the direction normal to the area (θ): 0°;
- Current intensity (I): 1.56 A.

The current intensity travelling through the inductor was determined using the first equation shown below, which considers the power and resistance of the electric current. In turn, the resistance in the inductor was obtained by applying the second equation [24]:

$$P = I^2 \times R \Leftrightarrow I = \sqrt{\frac{P}{R}} \Leftrightarrow I = \frac{409.07}{167.47} = 1.56 \text{ A}$$

$$R = \rho \times \frac{l}{S} = 1.72 \times 10^{-8} \times \frac{1.04}{1.068 \times 10^{-10}} = 167.47\ \Omega.$$

Relatively to the above equations, the value of the power in latter presented, the value of the resistivity (ρ) of the inductor corresponds to copper, namely 1.72 × 10^{-8} Ω·m [27], the inductors length (l) is measured in the 3D model of the component in Solidworks®, and S represents the cross-sectional area of the inductor. The field strength value is estimated by:

$$H = \frac{I}{2\pi r} = \frac{1{,}56}{2\pi \times 1.05 \times 10^{-2}} = 23.69\,\frac{\mathrm{A}}{\mathrm{m}},$$

where r is the solenoid radius. Once all the values that make up the equation have been determined, the frequency of the electric current that the generator needs to generate can be calculated as:

$$f = \frac{1}{\pi \times (4.65 \times 10^{-3})^2 \times 5.60 \times 10^3 \times 1.69 \times 10^5} = 155{,}372.17\ \mathrm{Hz} = 155.37\ \mathrm{kHz}.$$

The power generated by the generator, required to heat the injection nozzle by electromagnetic induction, can be estimated analytically. For this application it corresponds to the case where a coil heats a cylindrical workpiece [24]. Initially, the power required to heat the workpiece is determined (P_w):

$$P_w = m \times c \times \frac{T_f - T_i}{t}.$$

The relevant variables are as follows:

- Mass of the workpiece to be heated (kg): This value corresponds to the sum of the mass of the injection nozzle and the area of the injection nozzle in which the inductor is installed;
- Specific heat of the workpiece (c): 470 J/kg°C [26];
- Initial temperature (T_i): 20 °C;
- Final temperature (T_f): 600 °C;
- Heating time (t): 45 s. This value was set because it is considerably shorter than the current heating time, in which heating up to operating temperature takes around two minutes.

Thus, with the values that make up the equation determined, P_w is calculated:

$$P_w = 0.060 \times 470 \times \frac{600 - 20}{45} = 363.47\ \mathrm{W}.$$

The power in the inductor (P_i) is obtained by including the electrical efficiency (η_{el}) and thermal efficiency (η_{th}) coefficients, in such a way that:

$$P_i = \frac{P_w}{\eta_{el} \times \eta_{th}} = \frac{363.47}{0.987 \times 0.90} = 409.07\ \mathrm{W}$$

$$\eta_{el} = \frac{1}{1 + \frac{D_1 \times \rho_1 \times \delta_1}{D_2 \times \rho_2 \times \delta_2}} = \frac{1}{1 + \frac{0.021 \times 1.72 \times 10^{-8} \times 5.00 \times 10^{-4}}{1.78 \times 10^{-2} \times 1.69 \times 10^{-7} \times 4.65 \times 10^{-3}}} = 0.987$$

in which:

- Solenoids diameter (D_1): 0.021 m;
- Workpieces diameter (D_2): 1.78 × 10^{-2} m. This value corresponds to the cylindrical zone in the injection nozzle;
- Electrical resistivity of the solenoid (ρ_1): 1.72 × 10^{-8} Ω·m (copper);
- Electrical resistivity of the workpiece (ρ_2): 1.69 × 10^{-7} Ω·m (steel) [27];
- Depth of penetration into the solenoid (δ_1): 5 × 10^{-4} m. Since the thickness of the tube that makes up the solenoid is small, namely 0.5 mm, it is considered that its entire section is travelled by the electric current;
- Depth of penetration into the workpiece (δ_2): 4.65 × 10^{-3} m.
- Thermal efficiency coefficient (η_{th}): 0.90. This coefficient corresponds to this application, specifically the heating of a cylindrical workpiece by a solenoid [24].

To acquire a generator capable of generating an electric current with the desired characteristics, several national and international companies specializing in electromagnetic induction heating systems were consulted, which offered several budgets, in different ranges of price, of electromagnetic heating systems. For the analysis, an option provided by Ultraflex Power Technologies was chosen, as this solution met the previously established project requirements, at a highly attractive cost. The system included the SMT-2/200 generator, with 2 kW of power and the capability to generate an electric current with a frequency between 30 and 200 kHz, which works together with the HS-4W external circuit, the WCA-1000-02 chiller capable of delivering a maximum flow rate of 5 l/min, and the pyrometer, among others.

3.2.4. Cost Analysis

The applicability of this solution is directly dependent on its economic viability, assessed through the payback period and its interpretation, considering its implementation in 60 Zamak injection machines that can be found in the company. The payback period is determined by the ratio between the total cost of implementing the system and the corresponding annual savings. The total cost of implementation is mainly made up of the cost of purchasing and implementing an induction heating system in a machine, approximately €8300.00, multiplied by the number of machines, which amounts to an approximate value of €500,000.00. The annual savings were estimated considering the reduction in consumption of high-wear components in the previous heating system, such as electrical resistors, nozzles, and injection tips, as well as production stoppages due to component replacement, unclogging of the injection nozzle, and defects in parts. The value determined was €65,000.00. Considering these two values, a return on investment of 7.7 years (approximately 7 years and 8 months) is determined, a period from which the project generates a profit to the company.

It should be noted that the lifespan of electromagnetic induction heating systems varies between 10 and 12 years, a figure that can vary considerably depending on the conditions of use, time period after which degradation of the system's components and equipment is expected, leading to their replacement and, consequently, an undesirable increase in the project's cost [24]. Thus, the payback period is reached before the end of the lifespan of the system. Consequently, the project was classified as an economically viable option.

4. Conclusions

The design of an electromagnetic induction heating system led to the conclusion that this technology can provide the desired heating characteristics. By generating an electric current through the generator and passing it through the inductor, a magnetic field is created, which causes a part of the injection tip, known as the heat generation zone, to heat up to 600 °C (required to achieve the desired nozzle temperature). This temperature was determined through a thermal analysis using the FEM. From here, the energy, in the form of heat, spreads by conduction through the rest of the tip volume, and from there to the nozzle, so that it is possible to reach 550 °C at the top of the nozzle. Nozzle top temperature measurement is made possible by using the pyrometer associated with the induction heating system, which directly measures the temperature of the injection nozzle. The system analyzes the measured value, enabling it to adjust its operations based on the target temperature. By this solution, the temperature reduction of the injection tip, from 620 °C when heated by electric resistance to 600 °C, would mean an increase in the useful life of this component, as well as the injection nozzle, particularly by reducing the deterioration of the nitriding treatment on the tip and nozzle, and thus extend the useful life. In the proposed heating system, electric current is supplied through an external circuit to a multi-coil solenoid-shaped inductor, which is optimized for heating cylindrical components. The design featuring five turns of copper tubing proved to be the most effective, ensuring uniform heat distribution. To achieve the necessary temperature, an Ultraflex Power Technologies (New York, USA) generator was selected, providing a current of 155 kHz and 410 W, based on thorough analysis. Implementing the system in the 60 Zamak injection machines was not carried out but it would imply a payback period of 7 years and 8 months.

It is important to acknowledge the limitations of this study due to the absence of experimental validation. While FEM simulations provide design guidelines and predictive capabilities, they rely on assumptions and boundary conditions that may not fully capture the complexities of real-world manufacturing environments. Future experimental studies will be essential to confirm the accuracy of the numerical findings and validate the practical feasibility of the proposed solution. Physical testing of the induction heating system should focus on verifying temperature distribution, heating efficiency, and potential improvements in production quality and component longevity. Despite these limitations, the results suggest that electromagnetic induction is a promising alternative to conventional heating methods, which offers advantages such as rapid heating, precise temperature control, and improved energy efficiency.

Author Contributions

J.P.M.P., R.D.S.G.C. and F.J.G.S.: conceptualization, methodology, software; J.P.M.P., M.S.K. and M.S.: data curation, writing—original draft preparation; J.P.M.P.: visualization, investigation; R.D.S.G.C. and F.J.G.S.: supervision; J.P.M.P., M.S.K. and M.S.: software, validation; R.D.S.G.C. and F.J.G.S.: writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

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