CZECH TECHNICAL UNIVERSITY
IN PRAGUE

FACULTY OF MECHANICAL ENGINEERING

BACHELOR’S THESIS

EQUIPMENT FOR REHEATING A COFFEE CUP BY INDUCTION HEATING

2022

Darshil Patel

BACHELOR'S THESIS ASSIGNMENT

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I. Personal and study details

Student's name: **Patel Darshil**
Personal ID number: **481170**
Faculty / Institute: **Faculty of Mechanical Engineering**
Department / Institute: **Department of Instrumentation and Control Engineering**
Study program: **Bachelor of Mechanical Engineering**

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Guidelines:

1. Create thermal model of coffee cup and calculate needed power
2. Create electromagnetic model of induction heating at FEM software and optimize parameters
3. Create device and design a temperature control method

Bibliography / sources:

[1] RUDNEV, Valery, Don LOVELESS, Raymond L. COOK a Micah BLACK. Handbook of Induction Heating, Second Edition. Second edition. Taylor & Francis, 2016. ISBN 1466553952.
[2] BENDER, Edward A. An introduction to mathematical modeling. Mineola, N.Y.: Dover Publications, 2000. ISBN 978-0486411804.
[3] NOVA K, Martin. Introduction to sensors for electrical and mechanical engineers. 1. Boca Raton: CRC Press, 2020. ISBN 9781003081692.

Name and workplace of bachelor's thesis supervisor:

Ing. Lubomír Musálek Division of electrotechnics FME

Name and workplace of second bachelor's thesis supervisor or consultant:

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Ing. Lubomír Musálek Supervisor's signature	Head of department's signature	doc. Ing. Miroslav Španiel, CSc. Dean's signature

III. Assignment receipt

The student acknowledges that the bachelor's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the bachelor's thesis, the author must state the names of consultants and include a list of references.

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ABSTRACT

Induction heating technology is nowadays the heating technology of choice in many industrial, domestic, and medical applications because of its advantages regarding efficiency, fast heating, safety, cleanness, and accurate control. the most drawback is that extreme difficulty is encountered when trying to go low-resistivity, non-ferromagnetic metals like aluminum and copper, which are commonly used for cookware in several societies. the dearth of ferromagnetic properties, leading to no hysteresis dissipation, and low resistivity of such metals leads to an impractically low resistance reflected through the work coil. The resultant impedance complicates inverter design, because it is just too low to be efficiently driven with conventional inverter topologies. This work explores various techniques that are proposed and/or applied to efficiently heat low-resistivity heating cup and also the associated limitations. A transformer-coupled series-load-resonant topology driven by a full-bridge inverter is proposed as a way of efficiently heating ceramic cup which has the copper coil within the base to heat the liquid within the cup within practical design constraints. The simulation of the facility loss from the induction pad to the mug is completed in Agros2D software with the required parameters. procedure of optimizing the work coil for improved efficiency is additionally presented together with the procedure of measuring coil efficiency. Advances in key technologies, i.e., power electronics, control techniques, and magnetic component design, have allowed the event of highly reliable and cost-effective systems, making this technology readily available and ubiquitous.

Keywords: Induction heating, Full bridge inverter, electromagnetic analysis, Agros2D simulation

ABSTRAKT

Technologie indukčního ohřevu je v současné době technologie ohřevu, která se volí v mnoha průmyslových, domácích a lékařských aplikacích, protože má výhody týkající se účinnosti, rychlého ohřevu, bezpečnosti, čistoty a přesné regulace. největší nevýhodou je, že při pokusu o použití neferomagnetických kovů s nízkým odporem, jako je hliník a měď, které se běžně používají pro nádobí v několika společnostech, se setkáváme s extrémními obtížemi. nedostatek feromagnetických vlastností, což nevede k žádnému rozptylu hystereze, a nízký měrný odpor těchto kovů vede k neprakticky nízkému odporu odráženému přes pracovní cívku. Výsledná impedance komplikuje konstrukci měniče, protože je příliš nízká na to, aby mohla být efektivně řízena konvenčními topologiemi měničů. Tato práce zkoumá různé techniky, které jsou navrženy a/nebo aplikovány k účinnému ohřevu nízkoodporového ohřívacího pohárku a také související omezení. Jako způsob účinného ohřevu keramického pohárku, který má měděnou cívku uvnitř základny pro ohřev kapaliny uvnitř pohárku v rámci praktických konstrukčních omezení, je navržena transformátorově vázaná sériově zátěžová rezonanční topologie poháněná měničem s plným můstkem. Simulace ztráty zařízení z indukční podložky do hrnku je dokončena v softwaru Agros2D s požadovanými parametry. Postup optimalizace pracovní cívky pro zvýšení účinnosti je navíc uveden společně s postupem měření účinnosti cívky. Pokroky v klíčových technologiích, tj. výkonová elektronika, řídicí techniky a konstrukce magnetických komponent, umožnily vznik vysoce spolehlivých a nákladově efektivních systémů, díky nimž je tato technologie snadno dostupná a všudypřítomná.

Klíčováslova: Indukčníohřev, Plněmůstkový invertor, elektromagnetickáanalýza, Agros2D simulace

Declaration of Authorship

I hereby declare that this bachelor's thesis has been written by me in person. All information derived from other works has been acknowledged in the text and the list of references.

In Prague:

Darshil Patel

Darshil Patel

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Chapter-1

Introduction

1.1 The process of Induction heating

New highly efficient technologies in the heater sector are creating a need for goods that are safe, economical, and use less power. Because of its precision in application, inductive heating has indeed been widely employed for a variety of applications ranging from metal heating through dairy fluids heating. Electrical heating systems have become the subject of numerous earlier studies due to their increasing prevalence in power networks and the implications for energy reduction through much more effective construction and optimization [1].

Induction heating is a method of bonding, hardening, or softening metals or other conductive materials. Induction heating provides an appealing mix of speed, uniformity, and control for many modern production processes [1-2]. It seems to be a non-contact method of heating that uses electromagnetism to heat an electrically charged substance. The alternate electromagnetic radiation causes a current known as eddy current in a small portion of the work piece known as the skin depth. Owing to ohmic energy losses, eddy current creates heat and serves as the primary source of heat in an induction heat treatment. The looping effect does contribute to heat production in a ferromagnetic material, although to a considerably lesser extent. The depth of something like the skin is described as the level at which the amplitude of the currents declines e -1 from its interface. Its depth is determined by the substance's conductivities, the wavelength of the transmitted electromagnetic field, and the magnetic characteristics of the material.

Since the 1920s, the basic principles of induction heating have been recognized and utilized to industry. During World War II, technology advanced quickly to fulfill pressing wartime demands for a quick, dependable technique to harden metal engine components. Recently, the emphasis on lean manufacturing practices and enhanced quality control has resulted in the rediscovery of induction technology, as well as the creation of finely regulated, all solid state induction power supply [3].

A semiconductor devices RF power source transmits an Ac supply through the use of an inductor basic induction arrangement. Recirculation the eddy currents inside one metal component when it is put into an inductor and exposed to a magnetic flux. These currents run against by the metal's electrical resistivity, producing precise and localized heat. This heating happens including both magnetic as well as nonmagnetic components and is commonly referred to as the "Joule effect," after Joule's first law [4].

1.1.1 Background of Induction Heating

Michael Faraday's development of understanding a conceptual framework in induction heating in which studies with two windings wound around an iron frame demonstrated that the induced electric potential (emf) in any closed loop equals the time rate of proportional to the flux through into the loop, within which seems to be the cumulative effect of the electromotive force in volts and is the flux in Webbers. For nearly a decade, this approach was applied in motors, generator, transformer, and radio transmissions.Melting metals was the first important use of induction heating in the nineteenth century. Initially, metal or electrically insulating induction furnaces were used [5].

1.1.2 Electromagnetic Induction Heating

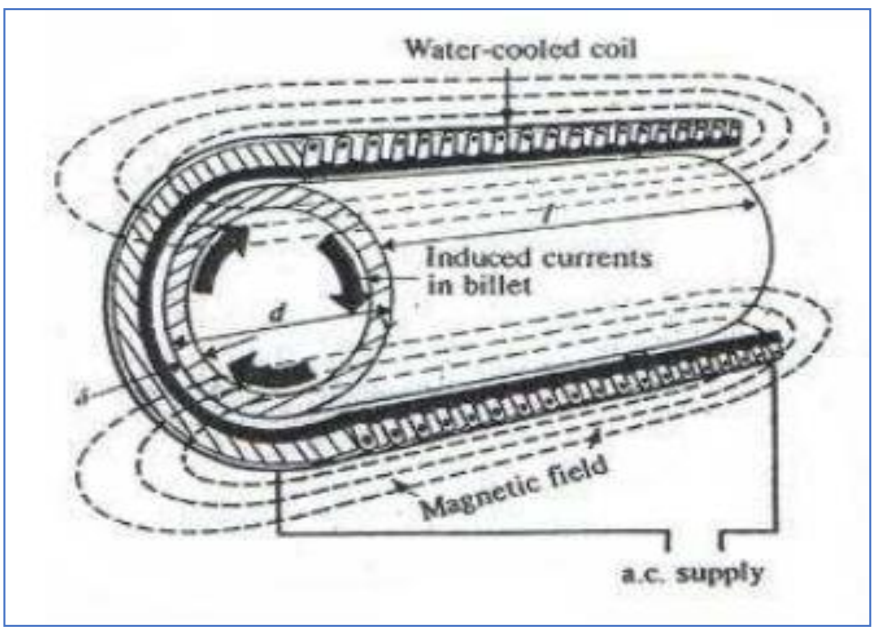

Figure 1Induction Heating Coil [5]

The creation of a voltage in a conductor is described by electromagnetic induction. It can occur in two ways: motional induction, in which a conductor travels in a magnetic field, and transformer induction, in which the circuit is fixed and the field fluctuates with time. Both effects may be accounted for by Faraday's law of electromagnetic induction, which connects the produced voltage to the rate of change of flux. When an alternating current is applied to a conductor, a magnetic field is created in the vicinity of the conductor. When a second electrical circuit is put in this magnetic field, it generates an electromotive force (emf) or voltage. When the circuit is closed, current flows through it [6].

1.1.4 Electromagnetic Induction Heating

Since the 1920s, the induction heating technique has been employed in manufacturing operations. As the saying goes, "necessity is the mother of innovation," and during World War II, the requirement for a quick technique to harden the components of the metal engine accelerated the development of induction heating technology. Today, we witness the implementation of this technology in our daily lives. Recently, the demand for greater quality control and safe production procedures has re-ignited interest in this technology. New and dependable techniques for implementing induction heating are being presented with today's cutting-edge technology [7].

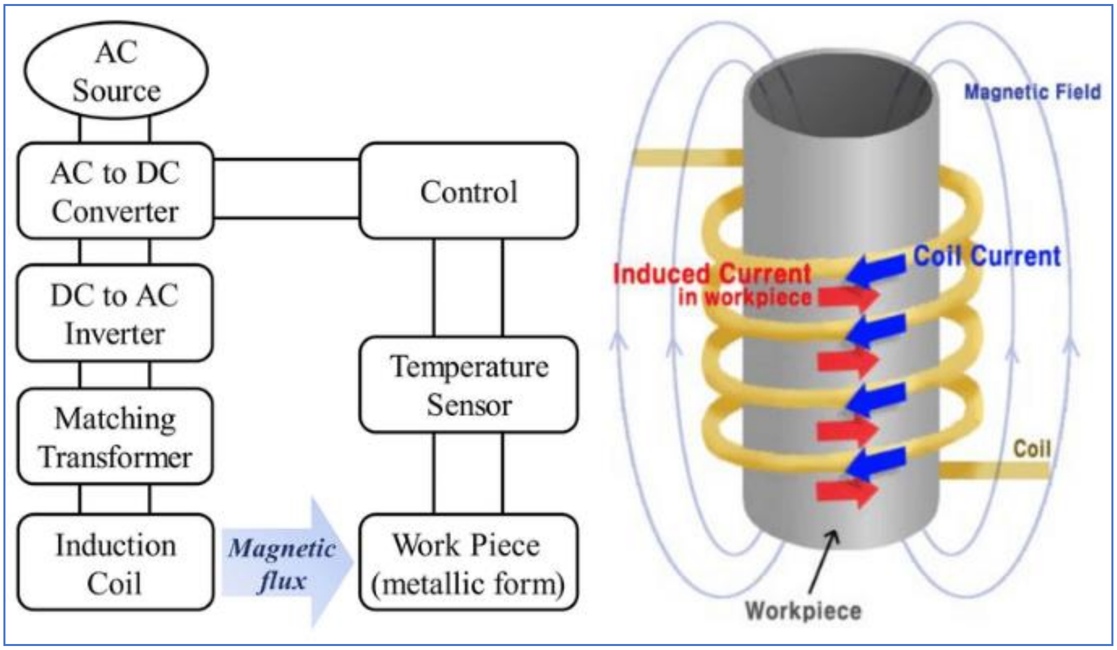

Figure 2 Block diagram and principle of Induction heating system [7]

The induction heating technique is based on a combination of electromagnetism and Joule heating. The quasi approach of heating an electrical conductor metal by creating eddy currents inside the material using the electromagnetic induction concept is known as induction heating. Temperature is obtained in the metal by the concept of Joule heating as the produced eddy current goes to against resistance of the metal [8].

1.1.5 Equation for Induction Heating

The frequency of inductive current influences the penetration depth of eddy current through into object. The effective depth of such current-carrying layers may be estimated by using induction equation below.

$$D=5000\ \sqrt{\rho/\mu f} \tag{1.1}$$

In the preceding equation,

'D' is depth in cm, ‘μ’ is material's magnetic permeability, ‘ρ’ would be the material's resistivity, ohm-cm, and 'f' is the AC fields frequency, Hz.

1.1.6 Induction Heating Vs Other types of Heatings

Figure 3 Other type of heating

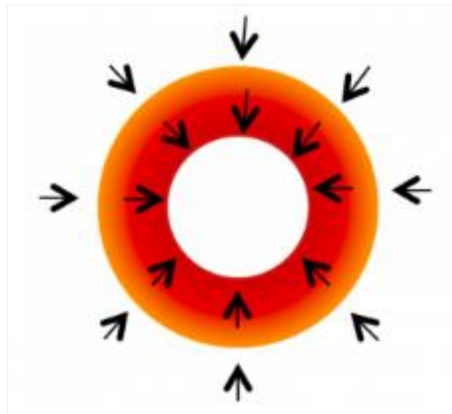

Figure 4 Induction heating

There are various ways to heat an item without using induction. Some of the most prevalent industrial methods are gas ovens, electric ovens, and salt showers. All of these processes rely on heat transmission to the material from the source of heat (burning, heat source, aqueous salt) via convection and radiation. When the product's exterior is heated, the heat is transferred through the material via thermal conduction.

Induction heated items do not dependent on convection or radiation to deliver heat towards the surface of the product. Rather, heat is created on the product's surface by the passage of current. The temperature from the product's surface is subsequently transported through the product via thermal conduction. The depth to which heat is created directly utilizing the induced currents at a specific depth is known as electrical reference depth.

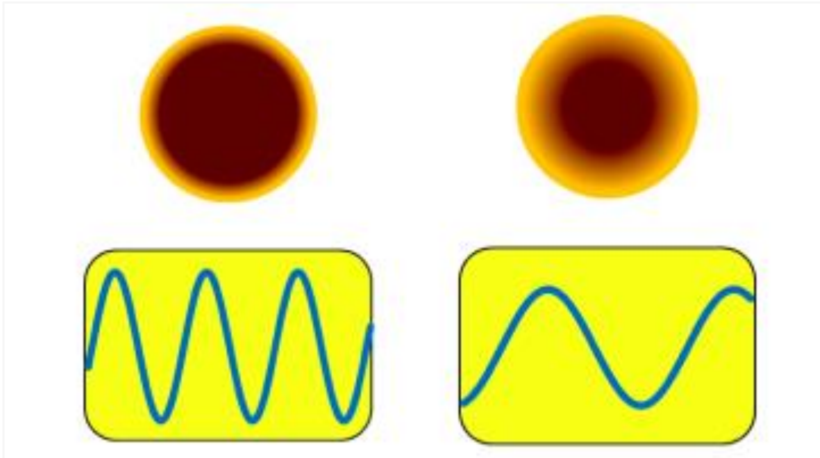

Figure 5 Electrical Reference Depth for High and Low Frequency levels

The frequency for an alternating current that flows through the work piece surface has a large influence on the electrical reference depths. Higher frequency current causes shorter electrical reference depths, whereas lower frequency current causes a greater electrical reference detail. This depth is also affected by the work piece's electrical or magnetic characteristics. Organizations in the Inducto-therm Group use electrical and physical processes to tailor heating solutions to individual products and solutions. Power, frequency, including coil shape is carefully controlled by the Inducto-therm Group firms, allowing them to develop equipment with excellent levels of process control and dependability irrespective of the use.

1.1.7 Design of Induction Coil

The design of an induction heating coil is critical to the coil's efficacy. The coil is utilized as an inductor in this case, and power is supplied in many forms. The flow of current induced in the material can be proportional to the turns of the coil.

In general, these coils are copper conductors, and different types of coils are utilized depending on the purpose as shown in fig.5. The most often used coil is multi-turn helical and the heating pattern width for this coil may be determined by the coil's turns. A single-turn coil is utilized when narrowband heating of material is required.

The helical coil or multi turn type is mostly used to heat a variety of metals. When only one area of the material has to be heated, a pancake coil is utilized, and an internal coil can be used to heat within bores.

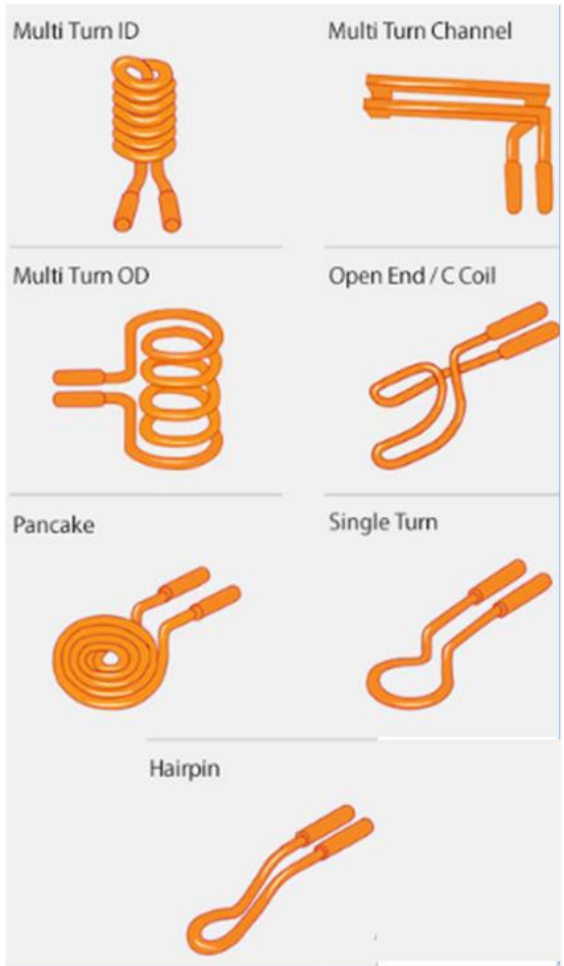

Figure 6 Mostly used configurations of induction coil

Overall heating of metal parts

Induction heating is a practical technology for bulk-heating metals. It substitutes big traditional ovens, which would have the drawback of taking a lengthy time to start up and shut off. Induction heaters were smaller in size than other furnace varieties and are ready to use right away. Unless a huge thermal mass has been heated, heating periods are normally brief - a few minutes. While induction heating occurs inside one surface region, heat is transferred to the remainder of the billet or block by heat conduction. Lower frequencies can indeed be employed by not attempting to limit the radiation to the surfaces in through heating.

Figure 7 Gear quenching by Induction heating coil

Heating from the outer surface

By using a high frequency, it is possible to obtain shallow heating depths and large power densities. Heat may be focused in a small area of a workpiece. This region's metallurgical properties may be altered without impacting the remainder of the material. As a consequence, a shallow hardened zone with a less brittle core is formed, combining the benefits of surface wear resistance and overall strength, as well as almost no deformation during the hardening process. Induction hardening saves energy (in comparison to conventional heating) and enables selective hardening since it warms a limited zone to a high temperature without impacting the remainder of the material. Surface heating cycles are often shorter than one second in duration due to the high power densities attained by high frequency (0.3 to 0.5s for 0.45 percent carbon steel). This is followed by a quenching cycle, which aids in the metal's retention of its hardened characteristics. Operating frequencies range from 3kHz to 450kHz, with induction surface heating systems reaching hundreds of kilowatts (depending on the application) [11]. Surface heating is often used in the car industry to harden tool tips, saw blades, and engine components (crank shafts).

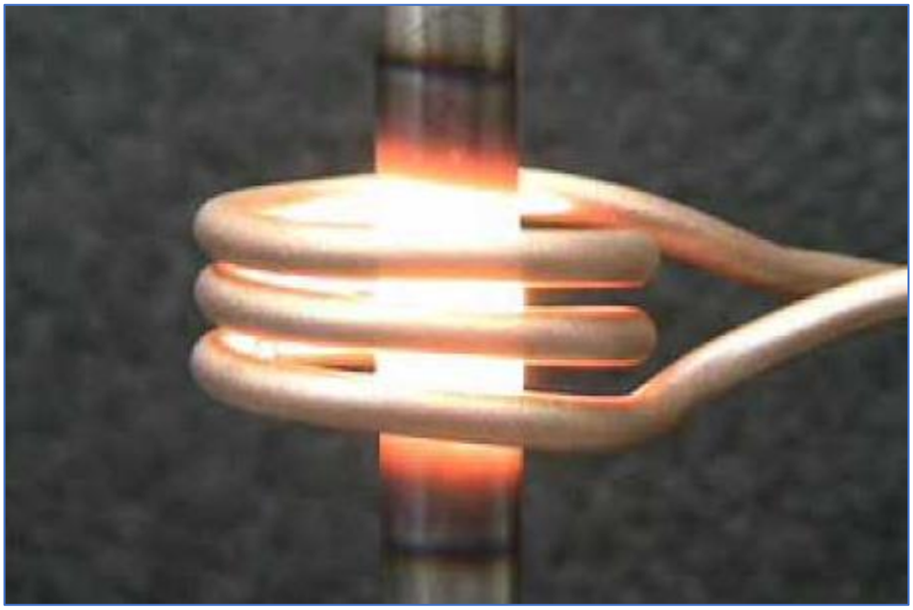

Figure 8 Heating the steel tube surface by Induction coil

Melting by Induction

There are no fundamental distinctions between melting by conduction and melting by induction. When compared to other methods of melting, induction melting provides the following advantages: rapid melting, with induction furnaces producing more than any other kind of furnace [12].

There are no excessive heat losses from the furnace, no smoke, dirt, or ash, and so the heating conditions may be enhanced. Automatic stirring caused by eddy currents in molten metal is advantageous for alloying purposes since it aids in the absorption of components and produces a homogeneous melt. By removing the risk of working with open flames and also by preventing gas leaks, the furnace creates safer working conditions. Special processes, like as vacuum melting, enable the production of alloys that are not possible to make any other way. Induction melting is often utilised in large-scale steel casting applications, where 2.5 MW I 500Hz facilities capable of casting 8 tonnes of steel are typical. Other melting uses vary from several hundred kilos to a few grammes (at low frequencies) (at high frequency). A frequent use of high frequencyTiny scale induction melting is used in the precious metals industry to melt and cast small amounts of platinum (20g to 120g) using less than 2kW at 140kHz [13].

Soldering by Induction

Induction soldering is a procedure that involves melting and pouring a filler metal (solder) into the joint interface.The filler metal (solder) used in this process has a lower melting point than the completed workpieces. Without making direct touch with the workpieces, induction soldering warms them in an RF (Radio Frequency) field.Induction soldering, unlike welding, does not entail melting the junctions. Induction brazing, on the other hand, is qualitatively different from soldering due to the higher temperatures involved.

Induction while soldering often results in a weaker union than brazing, this is often a desired outcome for many applications, particularly when working with delicate electronics or tiny components. Induction heating is the ideal choice since it enables precise control over the soldering process and eliminates thermal stress [14].

Brazing by Induction

Induction brazing is a method that uses induction heating to connect two or more metals. Induction heating generates heat without the need of touch or flame. When compared to conventional torch brazing, induction brazing is more localised, reproducible, and simpler to automate.Although induction brazing has existed for a long period of time, it is only now gaining popularity owing to developments in induction heating power supply.Induction brazing operates on a similar concept to that of a transformer, with the inductor acting as the main winding and the component to be heated acting as a single turn secondary winding.

The primary benefit of induction brazing is the precise localization of heat. The induction heating coil may be put directly on the joint, producing a more constant amount of heat than a torch. Additionally, induction brazing is more reproducible than conventional brazing. Induction brazing offers a more predictable heat profile (basically, the amount of heat applied over time) than conventional brazing and may be automated. It is not as dependent on the operator's abilities as it is on the torch brazing.Induction brazing is a relatively new method that has not yet gained widespread use. It is gaining favour among manufacturers, though, and is projected to continue growing in the next years.

Induction brazing is a method of joining metals that includes nickel, copper, cobalt, titanium, and steel. Induction brazing is also possible with non-metals such as ceramics, graphite, and glass. Due to its concentrated heat and ability to connect incompatible metals and alloys without melting them, it is an excellent method for joining dissimilar metals and alloys. Due to the fact that induction brazing utilises an electromagnetic field rather than a flame, it may be employed in a variety of locations where flame brazing is either impossible or dangerous [14-15].

Induction Cooking

Although induction technology has been used in cooking since the early 1900s, it has only recently acquired widespread acceptance in America. Manufacturers are currently focusing their efforts on developing more affordable and energy-efficient variants, which are gaining appeal worldwide.

Induction cooktops generate heat directly from the pots and pans, rather than via an electric or gas element. It boils water up to 50% quicker than a gas or electric kettle* and maintains a constant, exact temperature. The surface remains reasonably cold, preventing spills, splatters, and the odd boil-over from burning into the cooktop, allowing for fast and simple cleanup.

Through magnetic induction, induction cooking employs electric currents to heat pots and pans directly. Rather of heating the cooking vessel by thermal conduction (a gas or electric element transmitting heat from a burner to a pot or pan), induction warms the cooking vessel directly. A current is fed via a coiled copper wire under the cooking surface, which generates heat by creating a magnetic current throughout the frying pan. Due to the absence of an external heat source, only the element in use will grow heated as a result of the heat transmitted from the pan. Due to the fact that less heat energy is wasted during induction cooking, it is more efficient than standard electric and gas cooking. As is the case with other conventional cooktops, the uniformly heated pots and pans subsequently heat their contents by conduction and convection [16].

Induction – curing of paint

Curing using induction heating catalyzes or starts structural changes at the chemical and molecular level in any polymeric material, including epoxies, phenolic, polyesters, and silicones. These materials are used in a variety of ways to bind, protect, seal, and insulate a variety of items [17].

1.2 Skin Effect

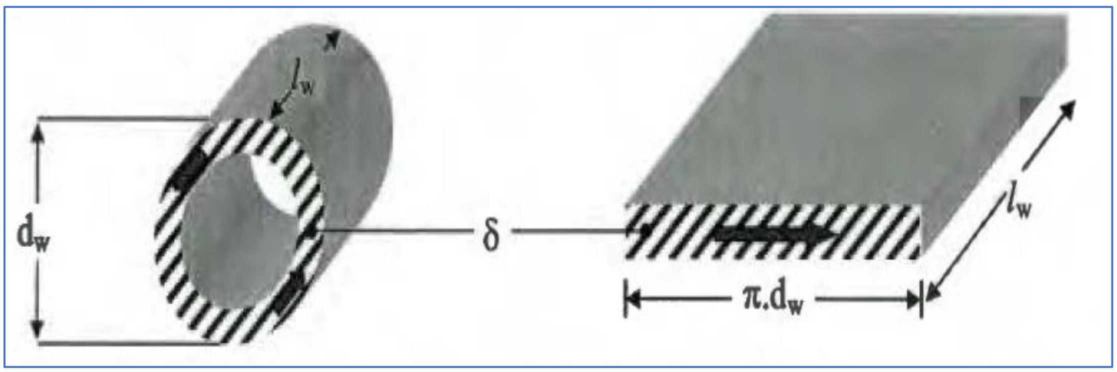

Figure 9 Skin Effect and skin depth (δ)

Induction heating is made feasible in part by the propensity of alternating current to concentrate in a peripheral layer (near the surface) of an electrical conductor.For example, a conductor is not uniformly distributed with electric current. The "skin effect" is a term for this phenomenon. Conductors have a lot of charge concentrated on their surface rather than in the center of them. When a lot of current is focused on the conductor's surface, the ohmic resistance increases. In noisy environments, a skin effect may be seen. The density of currents on the conductor's surface increases somewhat at low frequencies, such as 50 Hz. Almost majority of the currents flow on the conductor's surface at high frequencies, such as radio frequency. Conductors that are conducting d.c. current (frequency=0) have a uniform distribution of the current [18].

The depth of the skin (δ) at which the eddy current will seems to be concentrated is given by:

$$\delta = \sqrt{\frac{\rho}{\mu_0 \mu_r \ \pi f}} \qquad (1.2)$$

Where,

δ = penetration depth or skin depth

ρ = work-piece resistivity

f = eddy current frequency

μ_0 =permeability of free space

μ_r = relative permeability of the work-piece

The current density has dropped to approximately one-third of its surface value at the skin's deepest level. High-frequency frequencies result in a steeper drop in current density than lower-frequency ones. Figure 7 depicts the skin depth.

The resistivity of most metals changes with temperature according to the relationship,

$$\rho_\theta = \rho_1 [\, 1 + \alpha_{20} (\theta - \theta_1) \qquad (1.3)$$

Where:

ρ_θ = The resistivity at temperature θ,

α_{20}= the temperature coefficient of resistance at room temperature,

ρ_1 =the resistivity at temperature θ_1

The coil is water-cooled in order to keep its resistivity constant by reducing the heatgenerated due to skin effect in the coil and the heat radiated from the work-piece. Anadditional loss is associated with magnetic materials such as steel namely, hysteresis loss [19].

1.3 Induction Heating Load

A cylindrical coil holds the workpiece in place. In order to keep the workpiece (d_w) and the coil (d_c) separated by an air gap, electrical and thermal insulation must be maintained. In the figure, the coil and the workpiece's physical structure may be seen in Figure 8 [20].

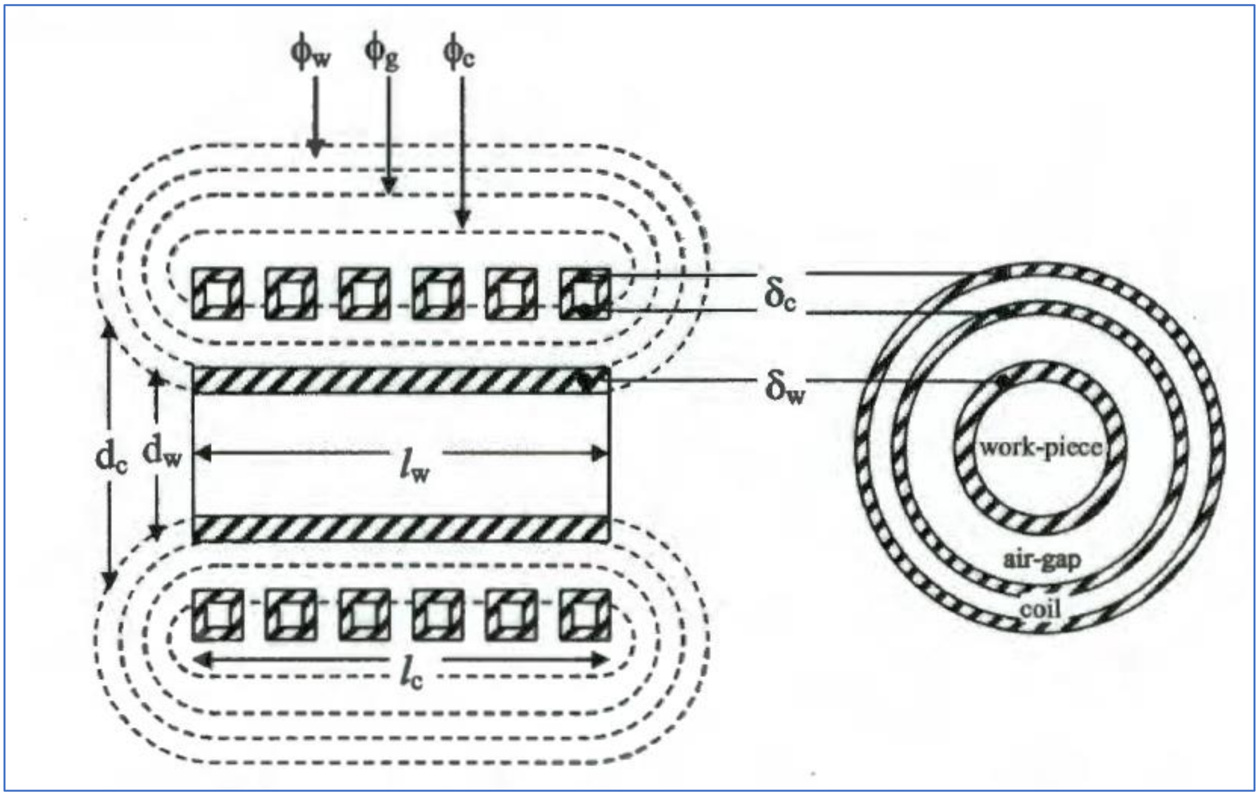

Figure 10 Physical structure of the coil and work-piece (using Baker's model)

1.4 Induction Heating Power Supply

An induction heating power source is a frequency converter that converts utility line frequency (50Hz) electricity to the single-phase power needed by the induction heating process. Reconductor and inverter components of this power supply convert alternating current (AC) from a single-phase or three-phase line frequency to alternating current (DC). Figure 9shows how this works:

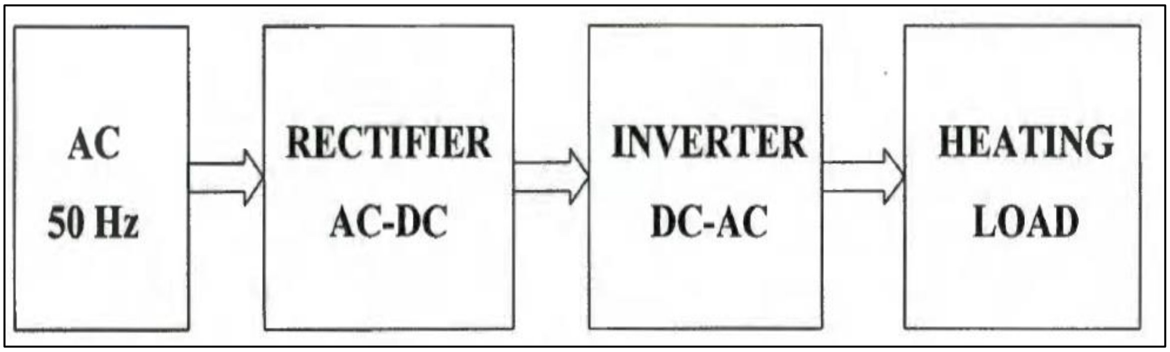

Figure 11 Converter, inverter and heater of a layout high-frequency power source

A thyristor, or SCR, is a solid-state switching device used in inverter circuits. Large thyristors are often employed for applications requiring great power and low frequency. Due to its capacity to be switched on and off extremely quickly with minimal switching losses, transistors are employed for low power or frequencies over 25kHz [21].

Chapter-2

Literature Survey

2.1 Induction heating topologies

Even though there are a variety of inverter topologies for induction heating (IH), most induction cookers use three main inverter topologies. A full-bridge inverter is used in both high-power, more expensive induction cookers and a broad range of industrial applications. As a result of this design's many active components and the need for current to flow through two switches at once, it has certain drawbacks. Cooktops and industrial equipment often use the half-bridge inverter as well. In a half-bridge inverter, only one switch is operational at a time. There are greater losses in high-power systems since the switching current for the same power level are larger, making it less desirable. By using these two topologies, the output voltage is regulated to a fixed DC bus voltage [22].

In the kitchen and in low-power industrial settings are used. Voltage clamping is not provided for these single switch types, like the full and half-bridge inverters, hence the switch is at risk of overvoltage damage in the event of wrong resonance conditions. A voltage-sourced inverter, such as a half- or full-bridge, is often used to drive an induction load. When the load is parallel-resonant, the resonant capacitor is connected across the inverter output, causing switching difficulties. Adding a second series inductor may address this issue, although this is not done in cooking because of the additional complexity. “A single-switch inverter design is more suited for driving the parallel resonant tank directly because of its current-sourced or multi-resonant nature [23].

Topologies have been presented that are more efficient, more reliable, have less component needs, and are more controllable than the fundamental designs. Improved power management and support for soft-switching were the most important developments in residential induction cooking equipment.The half-bridge inverter mentioned in might benefit from a number of improvements to increase soft-switching and control capabilities. This allows for zero-voltage and zero-current switching of main switches over a large working range thanks to the extra branch. Soft-switching is still possible because to the wide range of power management. To achieve zero-voltage turn-on, it allows the inverter to run at unity power factor while still charging device capacitances.

The auxiliary switch is used to bypass the extra capacitor once it has been connected in series with the resonant tank through the additional capacitor. As newer high-speed IGBTs give less advantage from zero current turn-offs, and as the lower power factor necessary to accomplish zero voltage turn-on is regarded acceptable in most household cooking equipment, these designs are seldom employed [24].

2.2 Components and factors affcting Induction Heating

Power supply, converters, and a quenching system comprise an induction heater. A fluctuating magnetic field is used to heat conductive and ferrous materials. The heated material is referred to as the "workpiece" in metal processing. Food is indirectly heated by conduction via a ferrous substance during preparation and cooking. We refer to ferrous material in this assessment for food processing as a heatpiece to distinguish it from metal processing. Foucault (eddy) currents are generated in the workpiece/heatpiece by the electromagnetic field, causing Joule heating [25]. An induction heating system is shown in Figure 12.

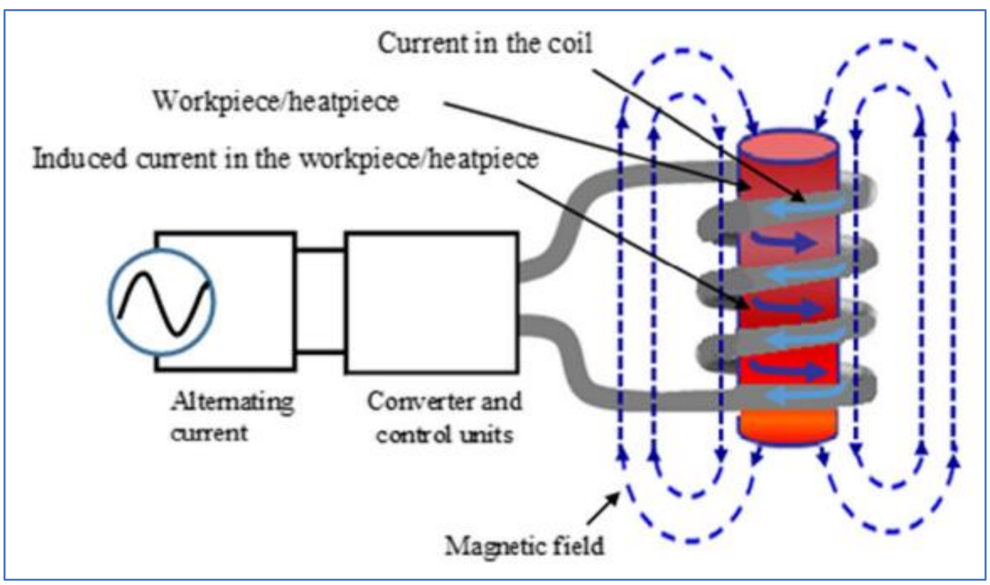

Figure 12 Main components of an Induction Heating system [25]

An induction coil's applied alternating current generates a time-varying magnetic field. When a magnetic field is created, it has a frequency that matches the coil current. As the current flowing through the induction coil varies, so does the shape of the coil and the distance from it. The hysteresis effect, in addition to eddy currents, may generate heat in magnetic materials during heating. As a result of this, the inductor generates a little amount of internal friction [26].

The temperature at which a material begins to lose its magnetic characteristics is known as a substance's Curie point [27]. Material kind and purity affect the curie temperature. A curie temperature of 353 to 360 °C for nickel and 770 to 850 °C for iron are the most common values. The frequency and kind of heating source separate induction heating from microwave heating. A magnetron is required for microwave heating, while coils and magnets are required to generate an electromagnetic field in induction heating. The most practicable frequencies for steel heating vary from 60 Hz to 450 kHz [25], depending on the size and material qualities of the workpiece/heatpiece. In the 2450 50 MHz [26] frequency range, microwave magnetrons produce the majority of their output. Organometallic compounds should absorb induction electromagnetic waves and then heat organic molecules indirectly via heat conduction before microwave energy may be absorbed directly. Using a microwave to heat thin and pointed bits of metal may cause arcing, which is a consequence of the fast heating of the metals within the microwave. Static, progressive multistage, and continuous and oscillation induction mass heating may be performed depending on the flow mode of the workpiece within the heating coils [27]. A low resistance to current flow may be achieved by cooling induction coils using air or water to maintain them at a low temperature [28]. The form of the coil is determined by the heatpiece/geometry. workpiece's Induction mass heating applications typically use cylindrical and rectangular multiturn induction coils [29]. Zinn and Semiatin [30] proposed numerous ideas for multiturn coils for components of different forms, such as round, rectangular, and shaped; pancake; and internal and spiral-helical [31, 32]. There are a variety of coils that may be used to heat pipes (e.g. heat exchangers) in the food business, but a frequent one is the multiturn and helical-shaped coil. In addition to the transverse field coil, a face inductor, and the flat spiral coil seen in Figure 13, different coil designs may be employed for flat surfaces [33-35].

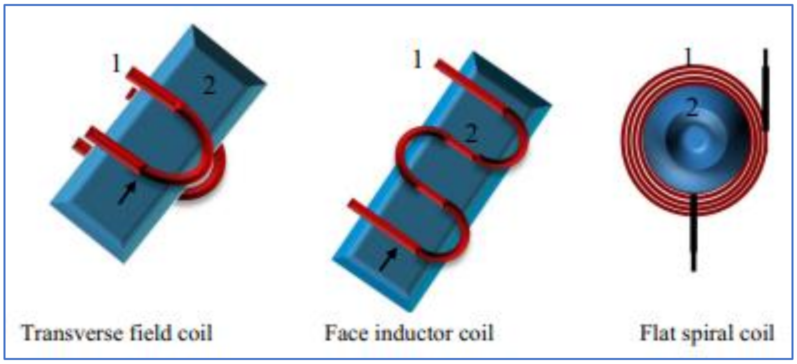

Figure 13 Induction heating coil configuration applications Coil : 1, coil; 2, workpiece/heatpiece [26-28]

2.3 Inductor Modulation Strategies and applications

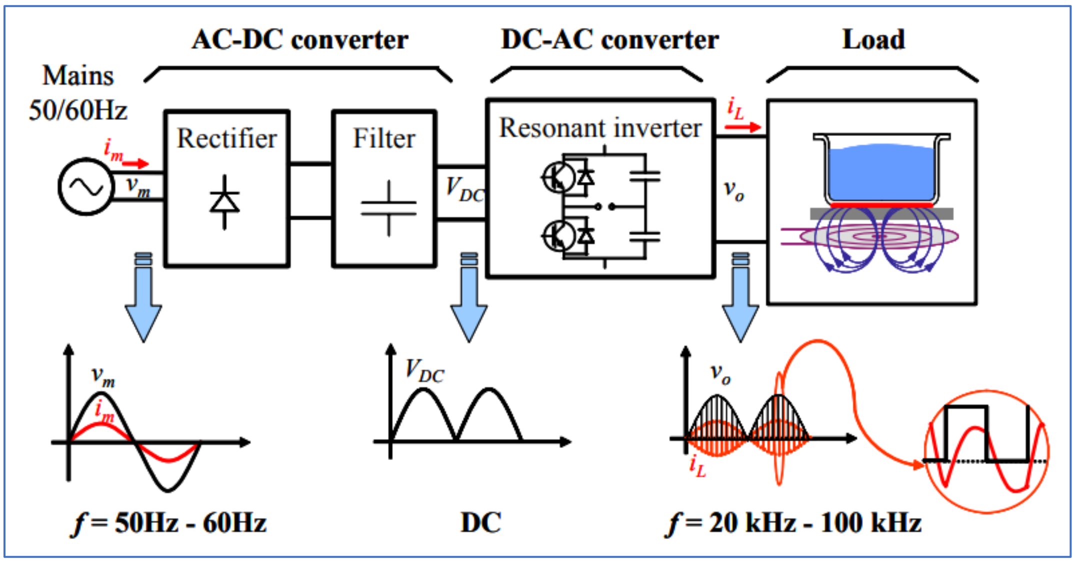

Figure 14 Diagram of the induction cooker's power electronics [36]

A diode bridge is used to convert a rectified mains voltage into an induction appliance's power source. When the input power factor is close to one, huge voltage ripples may be tolerated by the bus filter. Using an inverter architecture, the induction coil obtains its alternating current (20-100 kHz frequency range). Appliance induction burners may now provide up to 5.5 kW of heat power in the home. On the power stage of a home induction device, the schematic diagram is shown in Figure 14.

In the late 1990s, resonant inverter topologies resulted in a compact hob that is compatible with conventional resistive cookers, replacing the separate box on the floor. It is common for hobs to be positioned above an oven, which necessitates a temperature of 75°C (167°F) being taken into consideration while building electrical components.

Induction hobs now often use resonant inverter topologies. Some of the most often used topologies are full, half, and two single switch inverter [36-38] topologies. The half-bridge topology is the most popular in the present market because of its cost-effectiveness and robustness.

It is common to find appliances that have two or four inductors. One inverter may be used for each burner in a multi-burner induction cooker, or one inverter can be used for two or more burners [39-41], which has benefits such as lower overall costs and better electronic utilization ratios. Single-output inverters are often used to periodically multiplex loads using electromechanical switches [42], resulting in low-frequency switching with poor power distribution and loud noise. Two solid-state switches connected in series with the load have a negative impact on efficiency [43], and there are power management issues when all loads are on.On the other hand, the same idea may be used to a half-bridge inverter, using electronics to their maximum capacity, this is a low-cost innovation that provides additional benefits, such as the ability to heat up rapidly and effectively."

The foundations of a full-bridge two-output inverter are the sharing of a common leg and the addition of two low-cost relays (S1 and S2) to parallel the independent legs when just one output is required. It's possible to configure the converter such that it can output either one or both outputs. Resonant capacitors Cr1 and Cr2 and snubber caps Cs1 through Cs6 are presented in the literature to guarantee that the principal switches function at zero volts. The reaserch details a variety of output voltages and load currents as waveforms under different operating conditions.In order to work successfully, domestic induction cookers must be able to handle power outputs ranging from 50 W to 5.5 kW. The inverter's operating frequency may be changed to adjust the amount of power provided to a series resonant load. More power is given at a lower frequency than at a higher one. As a side note, domestic induction heating [44-46] often employs SW and ADC controls. Low-power controllers suffer a decline in output power when the switching frequency is increased, resulting in a loss of efficiency in these devices.It has been discovered that the most effective switching frequency may be reduced using PDM (Pulse Density Modulation) [47-50]. The inductors receive current at different intervals in the PDM, which allows it to regulate power consumption.Some limitations include the fact that the power is delivered in pulses of low frequency, which may create difficulties with flicker controls and ineffective heating of vessels.[51, 52] Discontinuous Mode Control (DMC) [aq] aims to achieve zero inductor current by lowering the power supplied to the load. [53] (discontinuous mode). This method's control variable is the amount of time that elapses between the gating signals from switches on the same leg. At steady state, the inductor current (iL) is zero and the output voltage (vo) is less than VDC/2 in discontinuous mode because both transistors and antiparallel diodes are off.

Switching at low frequencies is enabled by the DM to control the smallest possible power supply voltage range. To put it another way, with this management, especially in the low-power rangeefficiency benefits may be gained. In addition, the stress on the semiconductors and the balance of losses in the devices stay constant in the converter.During the test, both the input and output current and voltages are recorded. A/D converters in digital controllers sample these signals.The non-recurring engineering costs of an application-specific integrated circuit (ASIC) are particularly attractive since inductive home appliances are made in considerable quantities. To test the digital functionality, prototypes constructed on an FPGA might be employed.

Digital strategy's scalability and agility are two of its strongest assets.Digital design tools, such as Photoshop, Illustrator, and InDesign, may also speed up the design process. To define the design at the functional level, a hardware description language is utilized (HDL). HDL-based designs may be ported to ASIC or FPGA implementations through synthesis, simulation, and verification. As a result, the design may be easily converted to a different process or changed to meet new needs. We provide numerous digital VLSI implementations of a controller of resonant inverters for induction-heated cooking equipment.

The use of induction technology to automatically identify a vessel's presence is possibly the most common feature of digital control. A host of new features have been added to ASICs. One of the most important characteristics of a reliable power control is that it is reliable. Power control is crucial in order to create a useful and efficient product. There are two common methods for setting the power reference level: capacitive sensors and knobs.

Because they want it to be reliable and constant, business users have high expectations for the output power of a business appliance.Power control relies on accurate real-time measurements of power. Another drawback of multiple-output converters is that they all use the same DC bus. In order to determine the power of each burner, the medium-high frequency band must be used to detect and analyze signals (between 20 kHz and 100 kHz) Twenty, twenty-four, twenty-five.

Rather of traditional discrete analog-to-digital converters that need high sampling rates and resolution, the ASIC uses first-order sigma–delta () analog-to-digital converters [54-57].The digital modulator, which is built in synthesizable VHDL, generates the gating signals for the power components.Registrations for switching time, pulse width, and dead time may be found in the register. A finite state machine (FSM), RAMA, is used to build QH and QL. There are a total of four in this group. S1 and S3 are the states in which the quantum hall and quantum levitator are active, respectively. State transitions are determined by comparing the values in the counters with those stored in the configuration registers.

The program's central command and control point is a register called MCON. The FSM is in a reset state when the MR bit of the control register MCON is set.To carry out modulation methods, Reg TS, Reg DT, and Reg D are dynamically modified in line with certain frequency modulation systems. The operating point of the triangle modulation may be adjusted according to the triangular law by varying switching frequencies. This causes the modulation's amplitude to fluctuate over time. A 3500-watt induction appliance operating at a 25-kHz frequency was explained by a ersercher where a peak of 82 dBV may be shown using the 50 kHz frequency as an example. To reduce the peak by 3,51 dBV, the triangle uses Fbase=25 kHz, Tjitter=6.4 ms, and Ajitter=1.72 kHz [58-60].

Chapter-3

Methodology

3.1 Design of induction heating system for reheating the Coffee Cup

After identifying the purpose of the chosen component , specimen to be heated (the coffee cup), and power needed to attain the desired temperature, induction heating power supplies are designed. There in next step, the coil's design must be optimized to effectively transfer the required energy to the workpiece. Once the coil and workpiece have been matched to the high-frequency power source, load circuit calculations are necessary. The induction heating power supply simulation and design is then carried out in order to have a better understanding of how it works and to verify the solution that was established in chapter 4.

The power losses were estimated using the equations given below for various temperatures between 40°C to 70°C. i.e, for 40°C, 50°C,60°C and 70 °C by using the equations 3.1 and 3.2.

$$P_1 = \frac{T_2 - T_1}{\frac{1}{\alpha_1 . S} - \frac{d}{.\lambda . s} + \frac{1}{\alpha_2 . S}} \tag{3.1}$$

$$P_2 = \frac{T_2 - T_1}{\frac{1}{\alpha_3 . S_2}} \tag{3.2}$$

Where P_1 and P_2 are the power losses at temperatures T1 and T2.

The Coefficient of Thermal Expansion α for the material of the coffee cup and the coffee.

The considered values are:

- $\alpha_1 = 1000\ W/m^2 . K$
- $\alpha_2 = 15\ W/m^2 . K$

3.2 Design Considerations

3.2.1 Components considered in modeling

Various components considered in modeling are as follows:

Resistors:

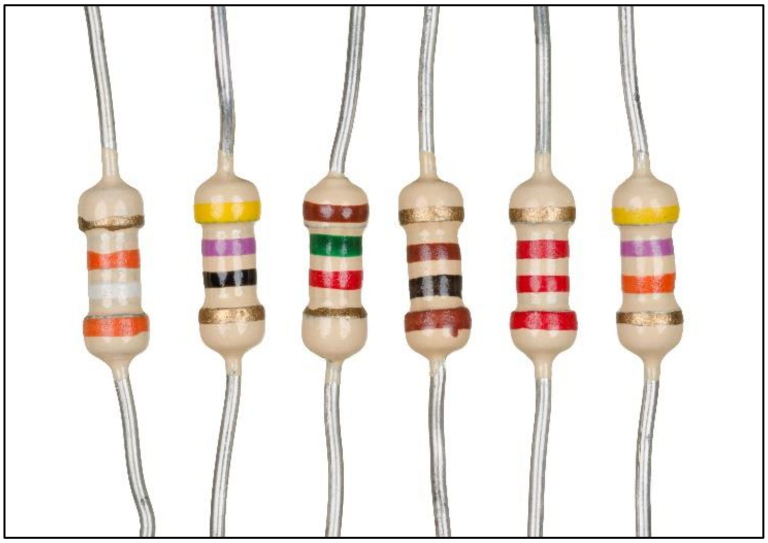

Figure 15 Resistors

A two-terminal component, also referred to as a circuit element, is used to measure and control a circuit's electrical resistance is a resistor. In electronic circuits, this component can be used to set signal levels, reduce the current flow, and divide voltages. Non-volatile, high-power, and heat-dissipating resistors are commonly used in different applications, such as testing the loads for generators and powering motor controls. They can also be utilized to adjust the operation of components, such as lamp dimmers and volume controls. In fixed-resistance design, the resistances change with the operating voltage and temperature.

A variety of electronic devices, such as electronic devices and electrical networks, are made up of components that are known as resistors. These are usually made of various compounds. A component's electrical function is determined by the resistance of its components. Usually, commercial resistors are made from a wide range of sizes and values.

Capacitors:

A capacitor is an electronic device that stores energy in the form of charged particles. It can also produce a difference in its voltage across plates. These devices are commonly used in power factor correction and resonance circuits.

Figure 16 Capacitors

A capacitor is an electronic device that consists of two parallel metal plates, neither of which is connected to each other and neither insulated by either air or a certain type of insulating material. These materials are usually separated by either plastic, ceramic, or wax paper. The insulating layer between these plates is called the Dielectric.

An insulating layer can prevent DC current from flowing through a capacitor. This layer then distributes the generated voltage across the plates, allowing the capacitor to function properly. Capacitors are typically made of metal plates. They are known as parallel plate capacitors.

Transistors:

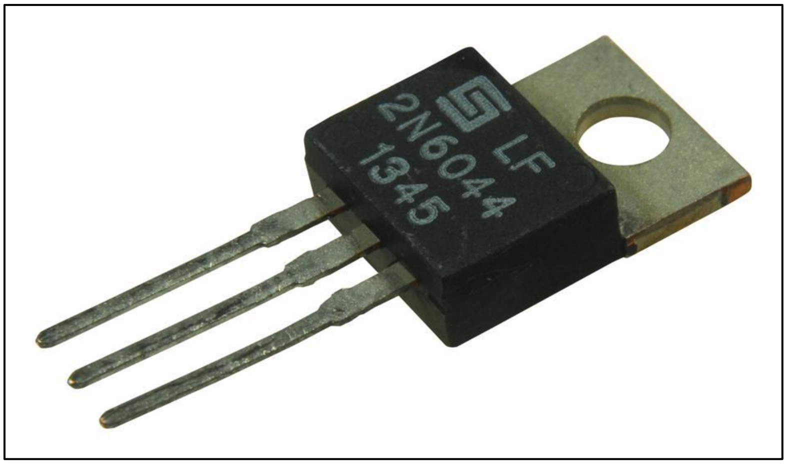

Figure 17 Transistors

A transistor is an electronic device that controls the flow of electrical signals. It can also function as a gate or switch for the generation electrical signals. In terms of its type, a transistor is typically made up of three layers. These are called terminals, and each of these can carry a current.

IRS2453D:

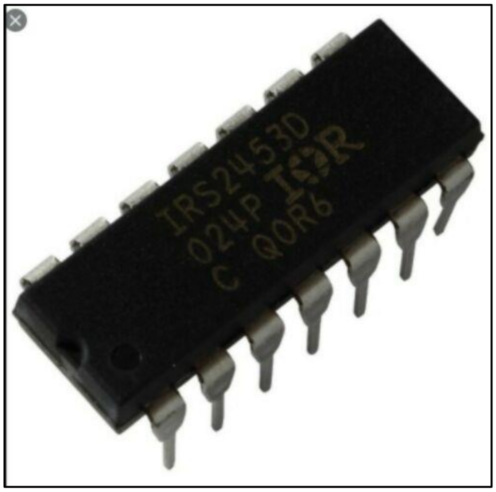

Figure 18 IRS2453D

The IRS2453D is a high-performance gate driver that uses the same technology as the IR2153. It features a full-bridge gate driver and a front-end oscillator that's similar to the industry standard 555.

Copper induction Coil:

Figure 19 Copper induction Coil

The basic induction-hardening setup involves using a copper conductor that's water-cooled. This ensures that the conductor doesn't get hot during the high-current phase.

Multimeter:

Figure 20Multimeter

A multimeter can measure different electrical properties, such as current, voltage, and resistance. It can be used to measure multiple electrical elements. These are referred to as "volt-ohm-milliammeters." The unit is equipped with either an ammeter, hertzmeter, or voltmeter.

Oscilloscope:

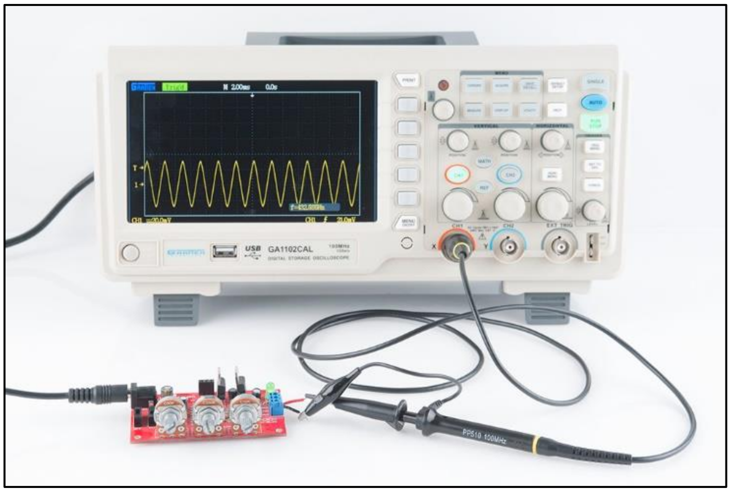

Figure 21Oscilloscope

An oscilloscope is a type of electronic device that can display and analyze electrical signals. It can also perform a graph analysis of the signal's instantaneous values.

Temperature sensor:

Figure 22Temperature sensor

A temperature sensor is an electronic device that measures the temperature of an environment. It then converts the data into electronic data. These can then be used to monitor the environment and record changes. Some of these require the presence of an object to be monitored.

DC power supply:

Figure 23DC power supply

A DC power supply is an electrical device that can provide current to a device under test. This type of electrical equipment can also be used to power various electronic devices, such as circuit boards.

3.3 The simulation software used

The Simulation software used for the present investigation is ‘AGROS 2D’.

3.4 The circuit construction

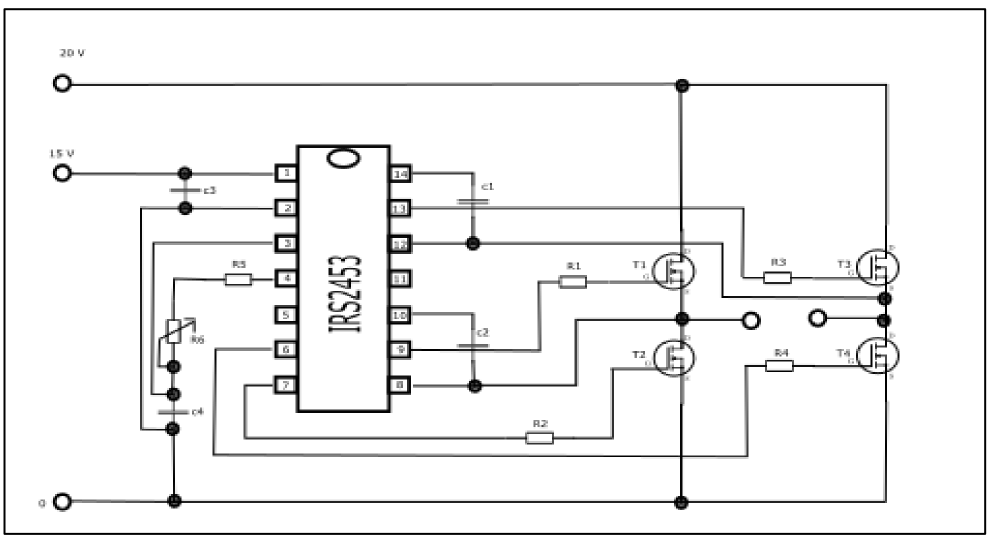

Figure 24 the circuit diagram

The circuit diagram considered for the present investigation is shown in figure 14 and the stages in practical circuit construction are depicted in figure 15.

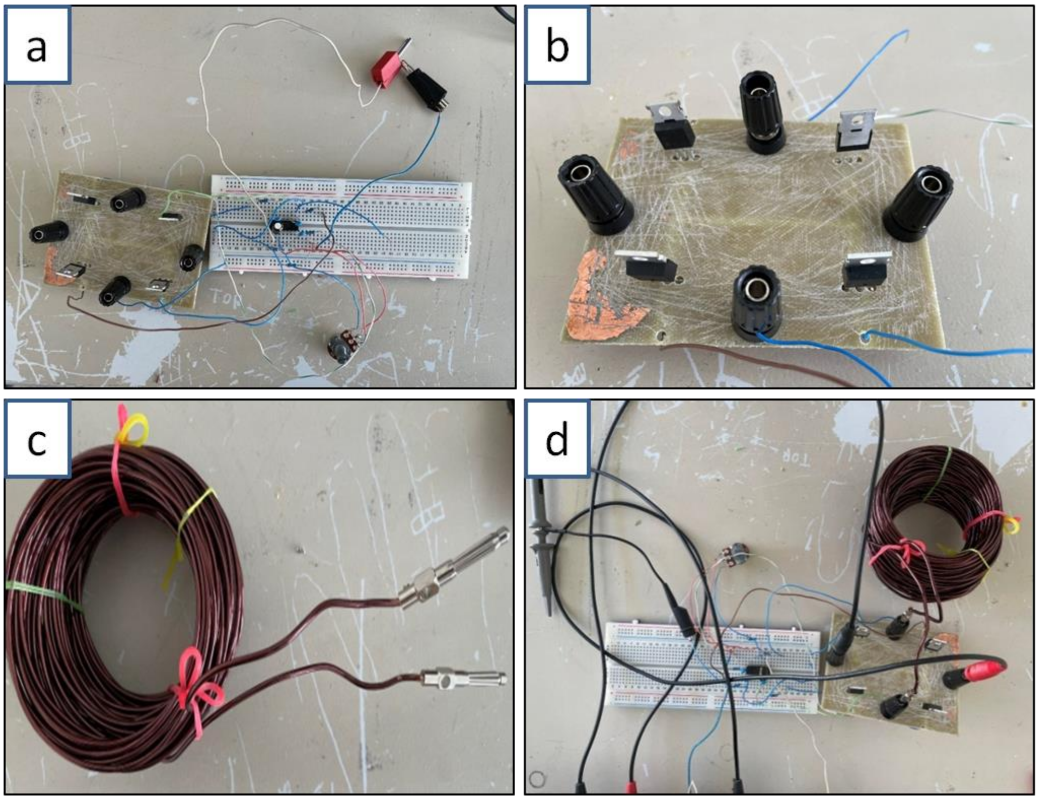

Figure 25 the Circuit Construction stages

Chapter-4

Results and Discussion

4.1 Calculations

First, we found the power losses from the equations given below for 40°C, 50°C,60°C, 70 °C:

Given values are:

- α_1 = 1000 W/m^2 . K
- α_2= 15 W/m^2 . K
- α_3= 30 W/m^2 . K
- λ (thermal conductivity) = 1.7

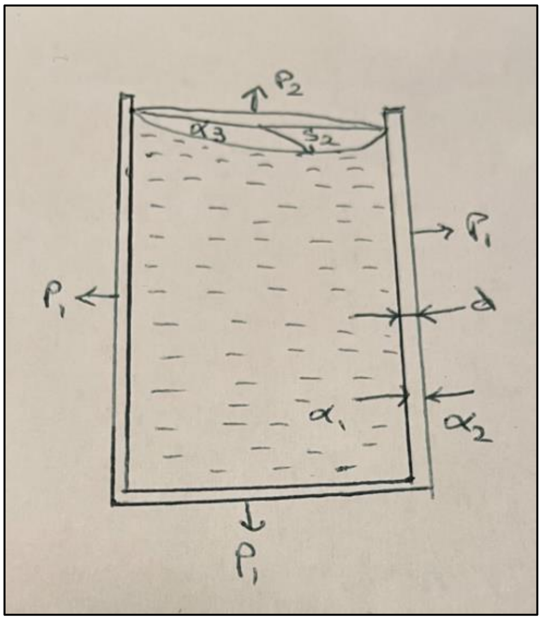

Figure 26 Parameters Considered

Equations:

$$P_1 = \frac{T_2 - T_1}{\frac{1}{\alpha_1 .S} - \frac{d}{.\lambda .s} + \frac{1}{\alpha_2 .S}} \tag{4.1}$$

$$P_2 = \frac{T_2 - T_1}{\frac{1}{\alpha_3 .S_2}} \tag{4.2}$$

Given Data:

- d = 1mm
- R_1 =40mm
- R_2 =45mm
- Room Temp = 20°C
- $S_2 = 4 \cdot \pi \cdot R_1^2 = 0.020$
- $S = 4 \cdot \pi \cdot R_2^2 = 0.025$

Calculated total power loss in at the given temp:

(NOTE: frequency should not exceed more than 100Khz)

Dimensions:

- Coil chamber = 175 mm
- Area of wire = 2 mm
- N turns = 87.5 turns (rounded off by 88)
- Current = 5 Amp
- Agros current = 437.5 Amp

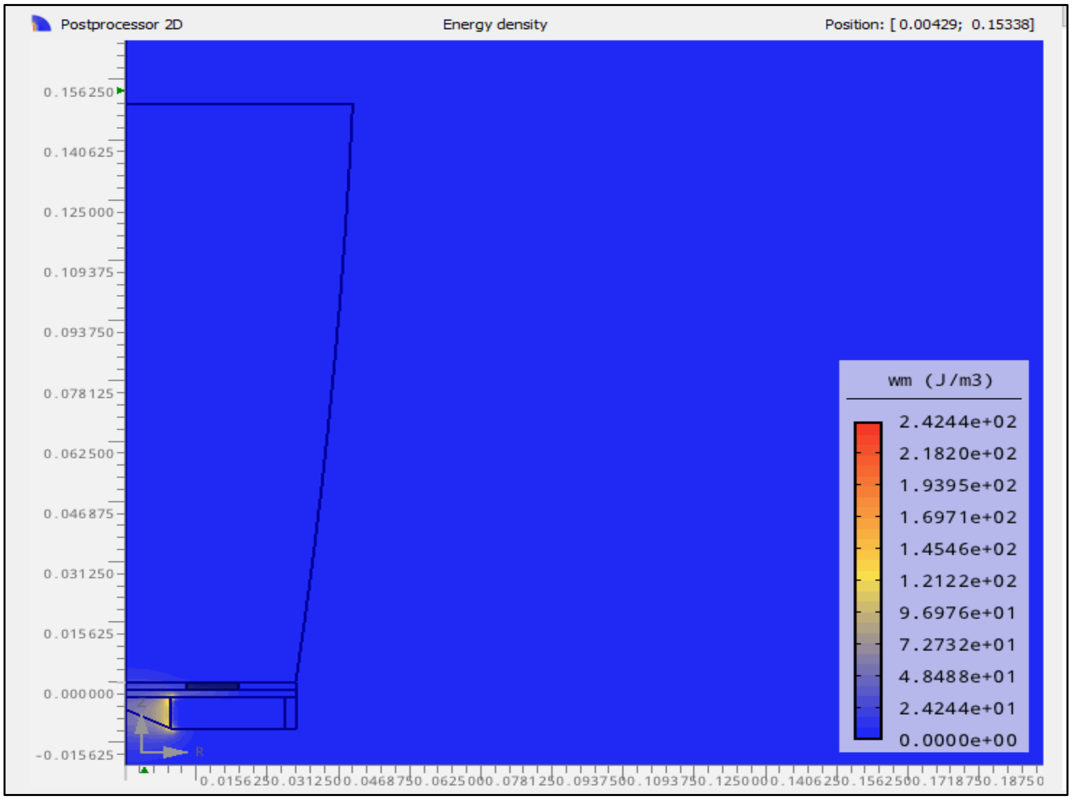

Figure 27 Results at 40°C

At 40°C:

- P_1 = 7.35W
- P_2 = 15.03 W
- P = 22.38W
- Calculated frequency from software is 11.9KHz

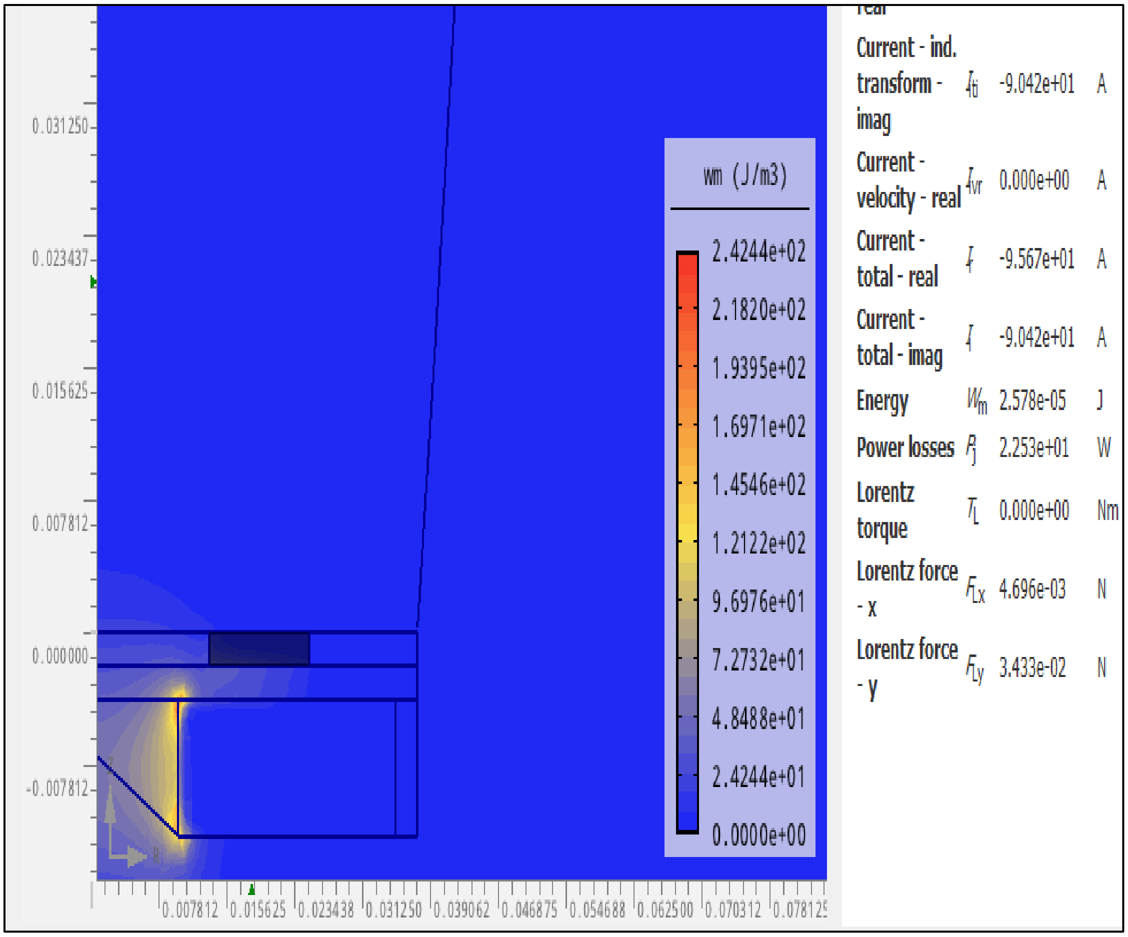

Figure 28 Results at 40°C

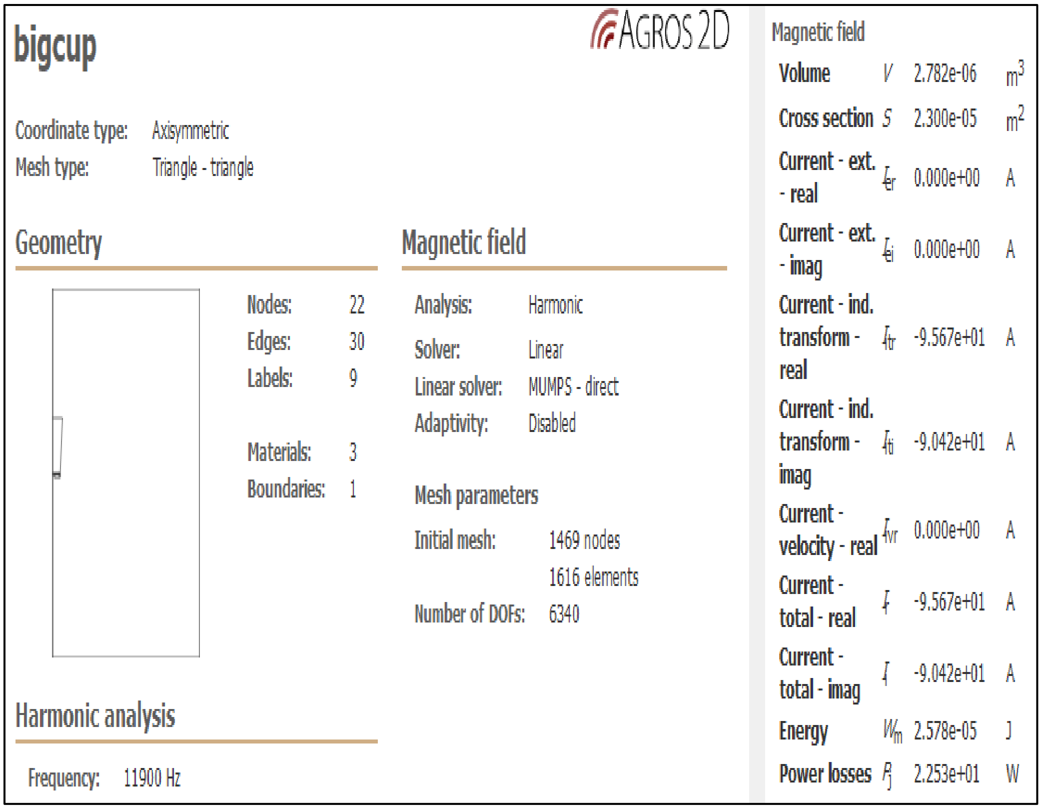

Figure 29 AGROS 2DResults at 40°C

At 50°C:

- P_1 = 10.90W
- P_2 = 22.55 W
- P = 33.45W
- Calculated frequency from software is: 19 KHz

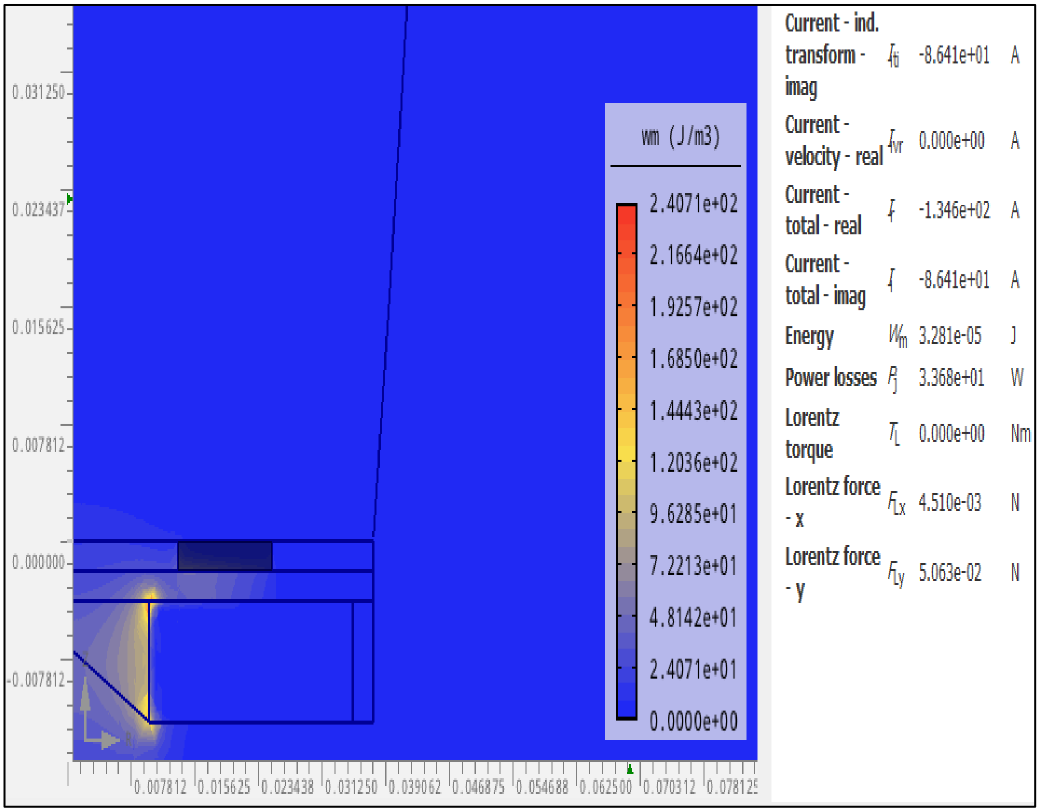

Figure 30 AGROS 2DResults at 50°C

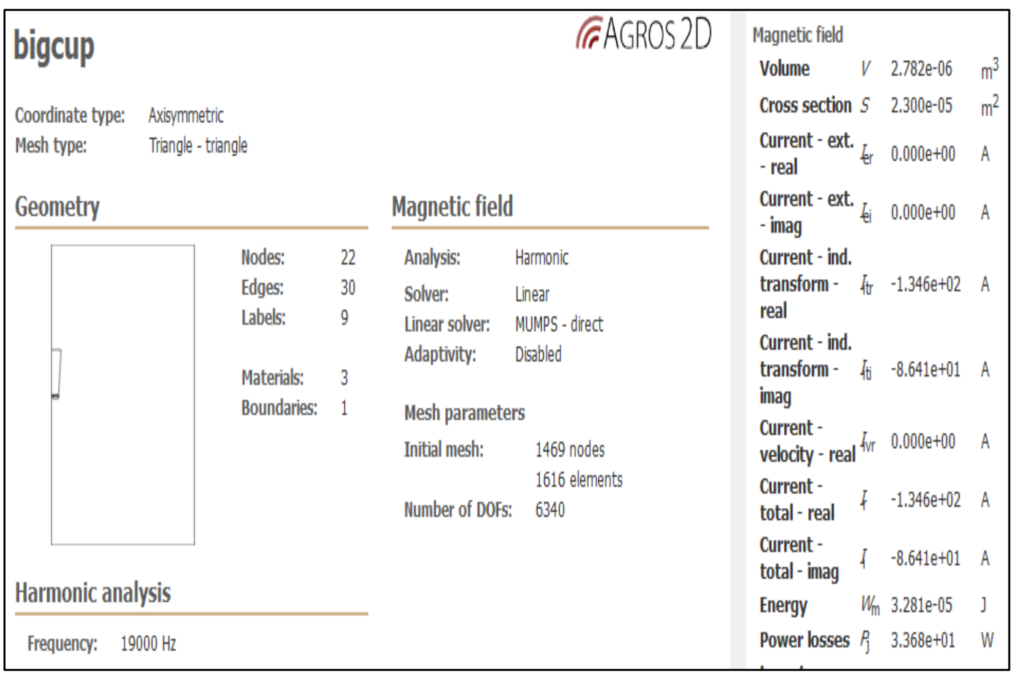

Figure 31 AGROS 2DResults at 50°C

At 60°C:

- P_1 = 14.54W
- P_2 = 30.07 W
- P = 44.61W
- Calculated frequency from software is: 31.5KHz

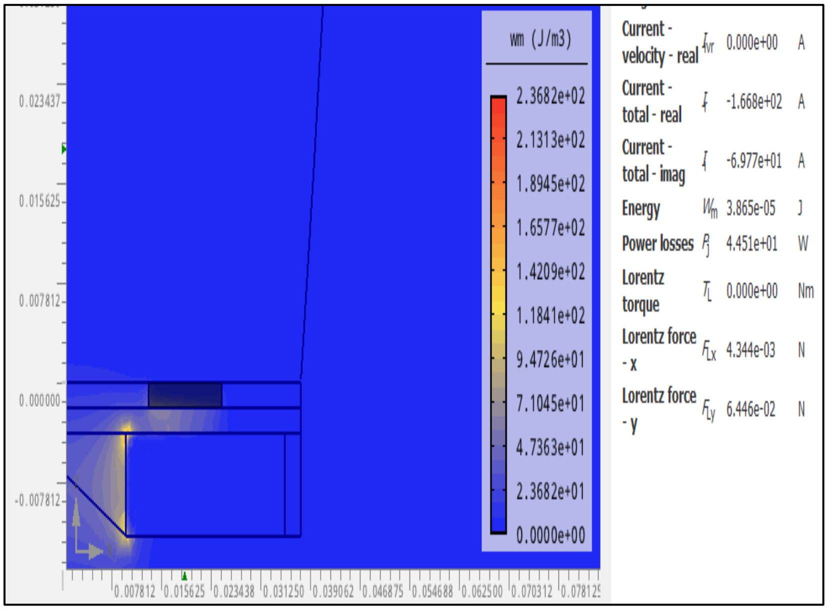

Figure 32 AGROS 2DResults at 60°C

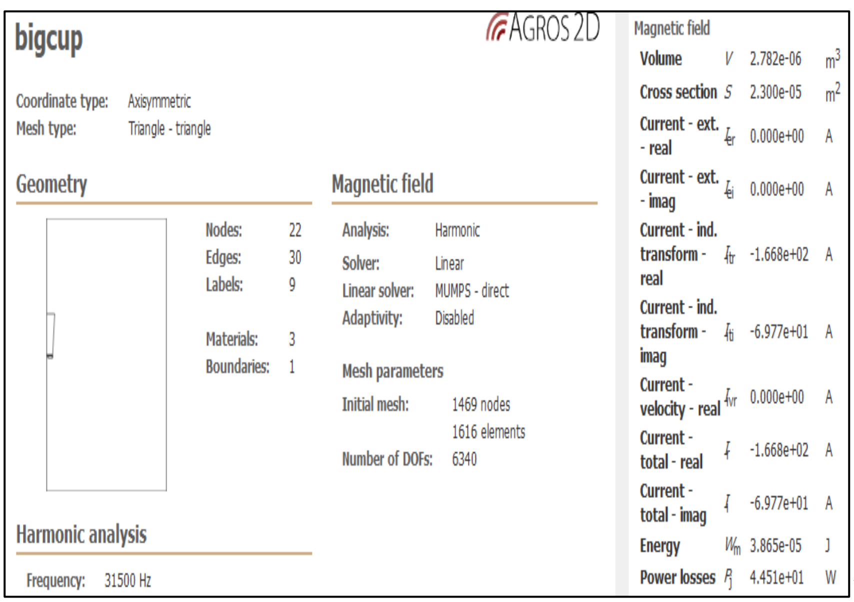

Figure 33 AGROS 2DResults at 60°C

At 70°C:

- P_1 = 18.18W
- P_2 = 37.59 W
- P = 55.77W
- Calculated frequency from software is: 54Khz

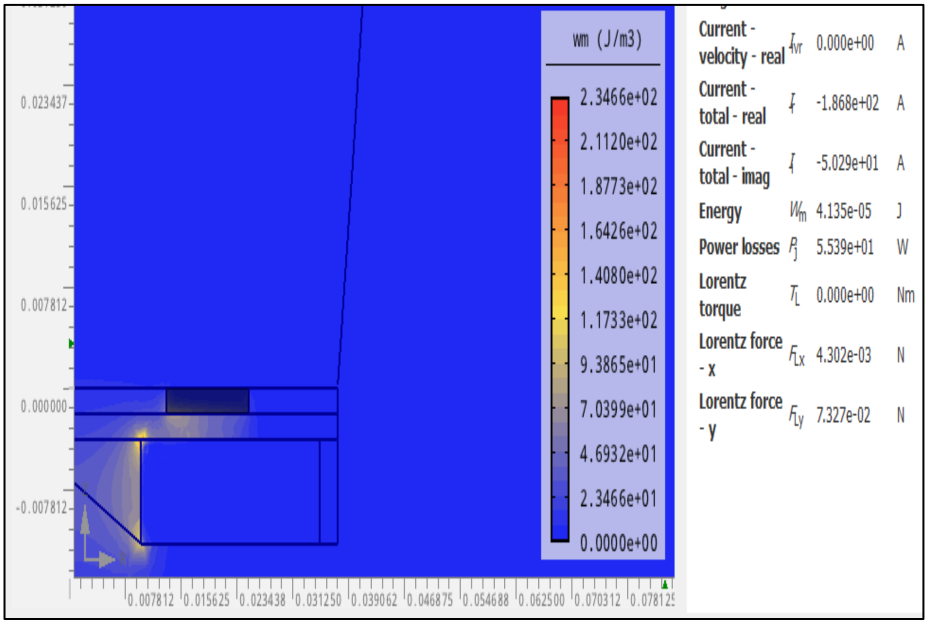

Figure 34 AGROS 2DResults at 70°C

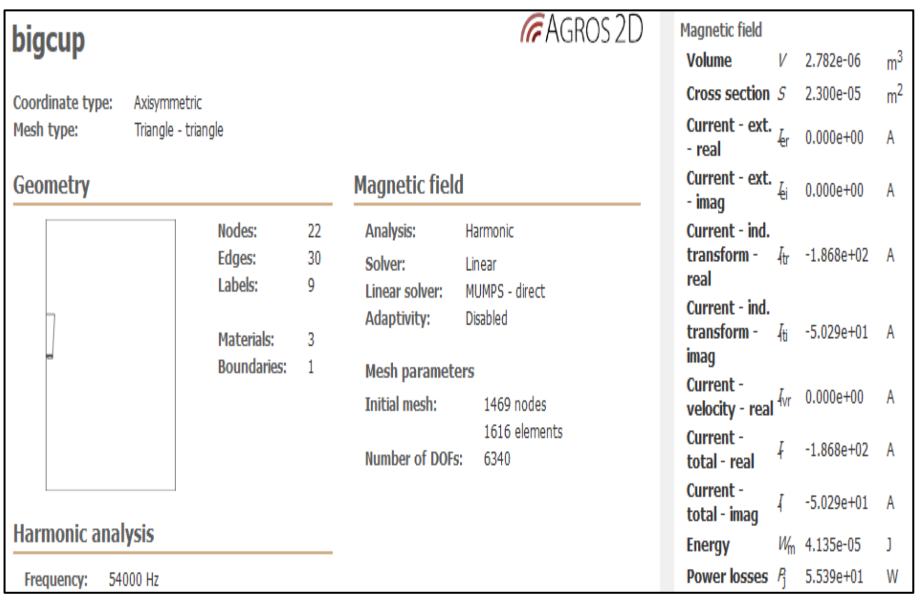

Figure 35 AGROS 2DResults at 70°C

Calculation table:

The following possibilities for dimension and parameter selection and the parameters highlighted in pink shade are selected.

Table 1 Possibilities for dimension and parameter selection

A(med)[mm]	A(wire)[mm^2]	N turns	Current 1[A]	Current 2[A]	Agros current 1	Agros current 2
105	1	105	2	2.5	210	262.5
175	1	175	2	2.5	350	437.5
175	2	87.5	4	5	350	437.5
175	3	58.33333	6	7.5	350	437.5
175	4	43.75	8	10	350	437.5
175	5	35	10	12.5	350	437.5
175	6	29.16667	12	15	350	437.5
175	7	25	14	17.5	350	437.5
175	8	21.875	16	20	350	437.5
175	9	19.44444	18	22.5	350	437.5
175	10	17.5	20	25	350	437.5
150	2	75	4	5	300	375
150	3	50	6	7.5	300	375
150	4	37.5	8	10	300	375
150	5	30	10	12.5	300	375
150	6	25	12	15	300	375
150	7	21.42857	14	17.5	300	375
150	8	18.75	16	20	300	375
150	9	16.66667	18	22.5	300	375

4.2 Comparison of results with the simulation model

Table 2 Calculated Practical Data

Temperature	Power	Resistor	Frequency
°C	W	ohm	kHz
40	22	33k	12
50	35	47k	19
60	44	56k	32
70	55	63k	54

AGROS 2D Simulated Data:

1) **At 40°C**

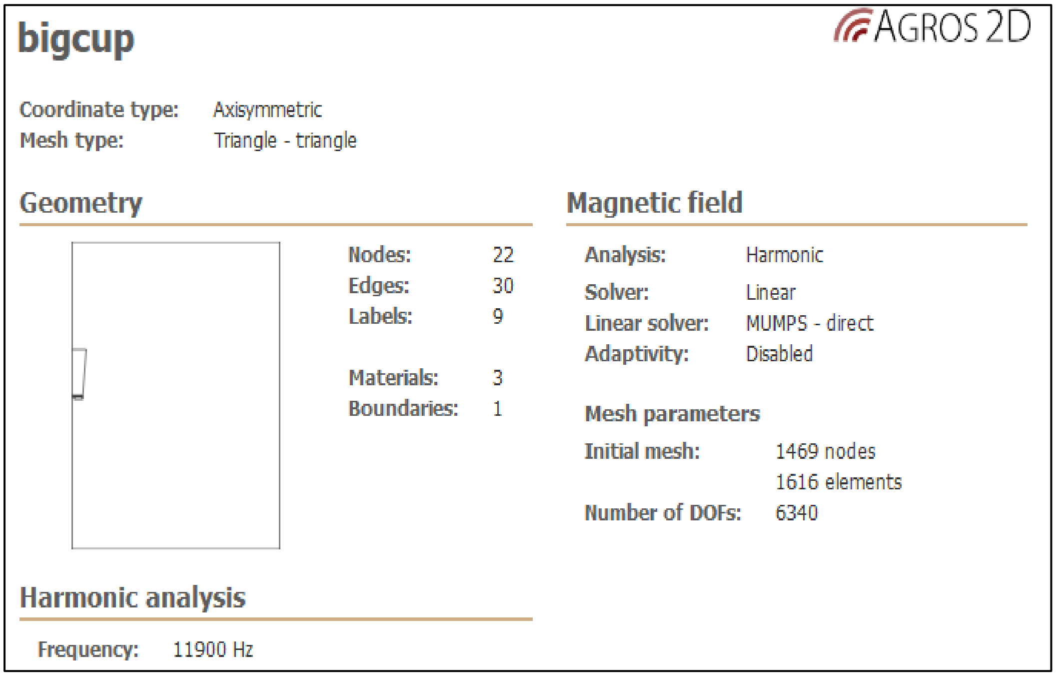

Figure 36 AGROS 2D Simulated Data at 40^0 C

2) **At 50 °C**

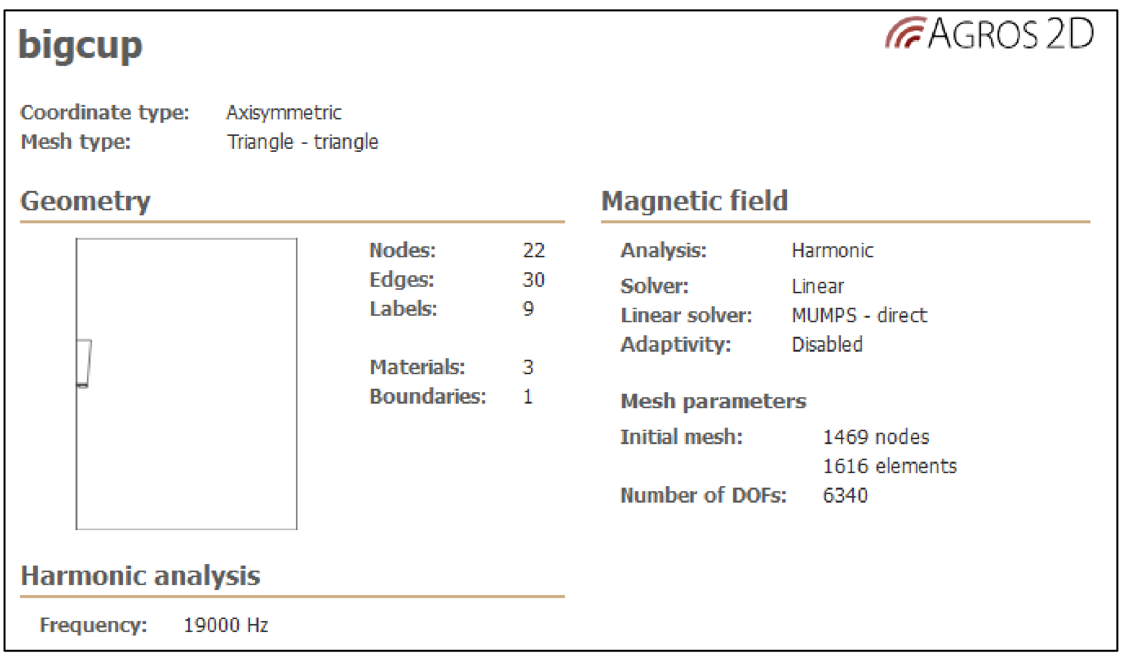

Figure 37 AGROS 2D Simulated Data at 50^0 C

3) **At 60 °C**

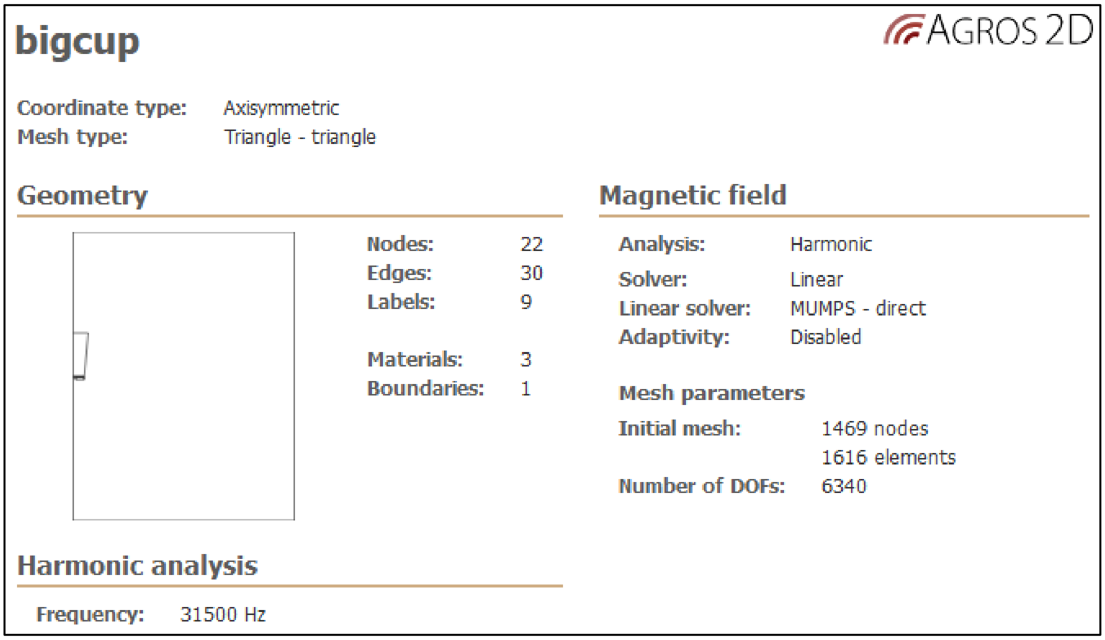

Figure 38 AGROS 2D Simulated Data at 60^0 C

4) **At 70 °C**

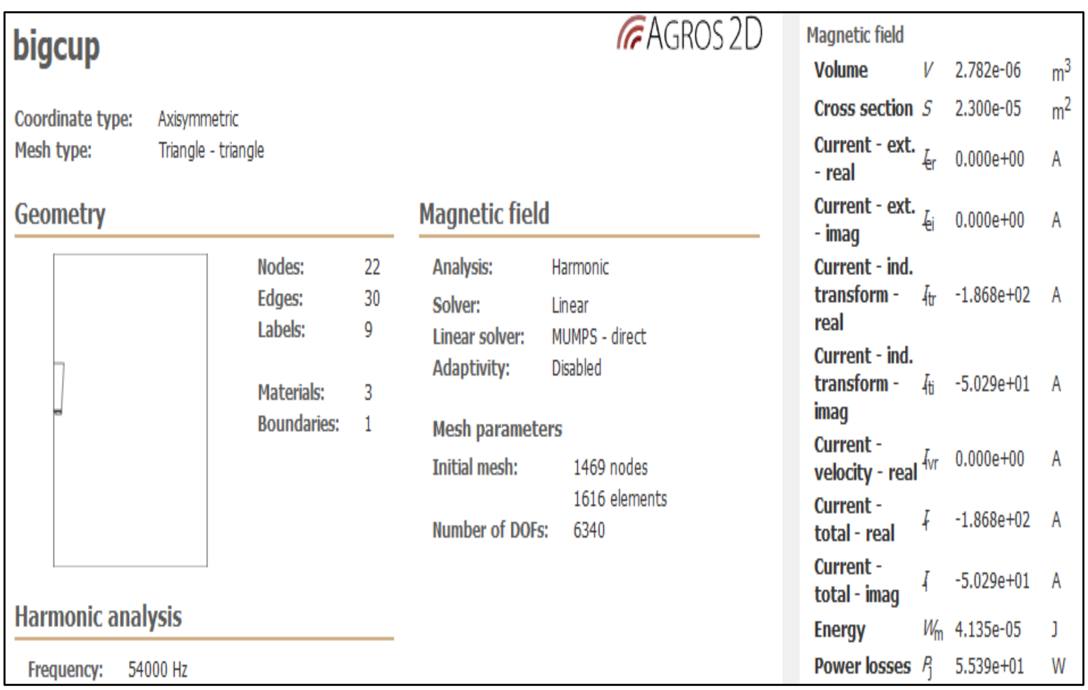

Figure 39 AGROS 2D Simulated Data at 70^0 C

Chapter-5

Conclusions

The present investigation presents numerical simulation of equipment for reheating a coffee cup by induction heating tool that can be used to describe the thermal behavior of a coffee cup during the process of Induction Heating. It is designed to provide a comprehensive view of the various aspects of the process Based on experimental investigation, and simulation through AGROS 2D software, the following conclusions are drawn.

- The investigations were performed successfully at four different temperatures considered for the study at 40^0C, 50^0C, 60^0C and 70^0C.
- The suitable possibilities for dimension were checked and various parameterswere studies through the present investigation and the best suitable parameter combination was selected.
- The concept of the presented investigation and the simulation allows users to perform complex calculations with minimal effort. Its boundary conditions are also taken into account the thermal properties of the supply source and the lining. This makes it ideal for applying in case of similar applications.
- This is useful in various engineering problems, such as those related to thermal heat transfer, heating and induction problems.
- The results obtained from the experimental investigation were compared with the simulation outcomes and the results were found to be in closely obtained without much deviation.
- Furthermore, there are more possibilities to make the equipment more compact and functional with adding of more features like smart control and IOT Equipped.
- The goal for this experiment was to see whether if the data achieved by the simulation process can be achieved by the Practical process or not. But by the appropriate calculations it was achieved precisely.

References

[1] Sun, D., Manoranjan, V. S., & Yin, H. M. (2007). Numerical solutions for a coupled parabolic equations arising induction heating processes. In *Conference Publications* (Vol. 2007, No. Special, p. 956). American Institute of Mathematical Sciences.

[2] Patil, T. G., Patil, A. A., &Patil, V. H. (2014). A Critical review on different coil configurations used for induction heating system. *International Journal of Engineering, Business and Enterprise Applications (IJEBEA)*, *7*(1), 35-39.

[3] Lucía, O., Maussion, P., Dede, E. J., &Burdío, J. M. (2013). Induction heating technology and its applications: past developments, current technology, and future challenges. *IEEE Transactions on industrial electronics*, *61*(5), 2509-2520.

[4] Liu, W., Chen, M., Xi, Y., Lin, C., & Liu, S. (2008, July). Thermo-mechanical analysis of a wafer level packaging by induction heating. In *2008 International Conference on Electronic Packaging Technology &High Density Packaging* (pp. 1-5). IEEE.

[5] Egan, L. R., &Furlani, E. P. (1991). A computer simulation of an induction heating system. *IEEE transactions on Magnetics*, *27*(5), 4343-4354.

[6] Murygin, A. V., Tynchenko, V. S., Laptenok, V. D., Emilova, O. A., &Bocharov, A. N. (2017, February). Complex of automated equipment and technologies for waveguides soldering using induction heating. In IOP Conference Series: Materials Science and Engineering (Vol. 173, No. 1, p. 012023). IOP Publishing.

[7] Ahn, C. H., Lee, J., Kim, D. J., & Shin, H. O. (2021). Development of a Novel Concrete Curing Method Using Induction Heating System. *Applied Sciences*, *11*(1), 236.

[8] Fujita, H., Uchida, N., & Ozaki, K. (2010). A new zone-control induction heating system using multiple inverter units applicable under mutual magnetic coupling conditions. *IEEE Transactions on Power Electronics*, *26*(7), 2009-2017.

[9] Hu, Z., & Li, J. Q. (1999). Computer simulation of pipe-bending processes with small bending radius using local induction heating. Journal of Materials Processing Technology, 91(1-3), 75-79.

[10] Semiatin, S. L. (1988). Elements of induction heating: design, control, and applications. Asm International.

[11] Geetha, V., &Sivachidambaranathan, V. (2019). An overview of designing an induction heating system for domestic applications. International Journal of Power Electronics and Drive Systems, 10(1), 351.

[12] Mühlbauer, A. (2008). *History of induction heating and melting*. Vulkan-Verlag GmbH.

[13] Dawson, F. P., & Jain, P. (1991). A comparison of load commutated inverter systems for induction heating and melting applications. *IEEE transactions on power electronics*, *6*(3), 430-441.

[14] Rudnev, V. (2016). Induction Heating and Heat Treating: Computer Modeling. In *Encyclopedia of Iron, Steel, and Their Alloys* (pp. 1835-1851). CRC Press.

[15] Rudnev, V., & Totten, G. E. (2014). Design and fabrication of inductors for heat treating, brazing and Soldering. *ASM International*, *4*, 619-32.

[16] Rudnev, V., & Totten, G. E. (2014). History and Applications.

[17] Honzicek, J. (2019). Curing of air-drying paints: a critical review. *Industrial & engineering chemistry research*, *58*(28), 12485-12505.

[18] Boglietti, A., Cavagnino, A., &Lazzari, M. (2010). Computational algorithms for induction motor equivalent circuit parameter determination—Part II: Skin effect and magnetizing characteristics. *IEEE transactions on Industrial Electronics*, *58*(9), 3734-3740.

[19] Jalloul, A., Trigeassou, J. C., Jelassi, K., & Melchior, P. (2013). Fractional order modeling of rotor skin effect in induction machines. *Nonlinear Dynamics*, *73*(1), 801-813.

[20] Cathey, J. J., Cavin, R. K., &Ayoub, A. K. (1973). Transient load model of an induction motor. *IEEE Transactions on Power Apparatus and Systems*, (4), 1399-1406.

[21] Chen, M. P., Chen, J. K., Murata, K., Nakahara, M., & Harada, K. (2001). Surge analysis of induction heating power supply with PLL. *IEEE Transactions on power Electronics*, *16*(5), 702-709.

[22] Koshti, A. K., &Rao, M. N. (2017, February). A brief review on multilevel inverter topologies. In *2017 International Conference on Data Management, Analytics and Innovation (ICDMAI)* (pp. 187-193). IEEE.

[23] Kranjc, M., Zupanic, A., Miklavcic, D., &Jarm, T. (2010). Numerical analysis and thermographic investigation of induction heating. *International Journal of Heat and Mass Transfer*, *53*(17-18), 3585-3591.

[24] Gao, K., Qin, X., Wang, Z., Zhu, S., &Gan, Z. (2016). Effect of magnetizer geometry on the spot induction heating process. *Journal of materials processing technology*, *231*, 125-136.

[25] Davies, E. J., & Barker, T. (1991). Conduction and Induction Heating. *IEE REVIEW*.

[26] El-Mashad, H. M., & Pan, Z. (2017). Application of induction heating in food processing and cooking. *Food Engineering Reviews*, *9*(2), 82-90.

[27] Heard, R., Huber, J. E., Siviour, C., Edwards, G., Williamson-Brown, E., &Dragnevski, K. (2020). An investigation into experimental in situ scanning electron microscope (SEM) imaging at high temperature. *Review of Scientific Instruments*, *91*(6), 063702.

[28] Velasco, S., &Román, F. L. (2007). Determining the Curie temperature of iron and nickel. *The Physics Teacher*, *45*(6), 387-389.

[29] Risman, P. (2009). Advanced topics in microwave heating uniformity. In *Development of packaging and products for use in microwave ovens* (pp. 66-107e). Woodhead Publishing.

[30] Zinn, S., &Semiatin, S. L. (1988). Coil design and fabrication: basic design and modifications. *Heat treating*, *12*(3), 32-36.

[31] Kolleck, R., Veit, R., Merklein, M., Lechler, J., & Geiger, M. (2009). Investigation on induction heating for hot stamping of boron alloyed steels. *CIRP annals*, *58*(1), 275-278.

[32] Acero, J., Hernández, P. J., Burdío, J. M., Alonso, R., &Barragdan, L. A. (2005). Simple resistance calculation in litz-wire planar windings for induction cooking appliances. *IEEE Transactions on magnetics*, *41*(4), 1280-1288.

[33] Lucian, S. G. (2014). Optimal design approach of inductors for mass heating processes. *International Journal of Application or Innovation in Engineering & Management (IJAIEM)*, *3*(11), 423-427.

[34] Sazak, B. S., Çetin, S., &Oncu, S. (2007). A simplified procedure for the optimal design of induction cooking appliances. *International journal of electronics*, *94*(3), 197-208.

[35] Qiu, L., Xiao, Y., Wang, S., Deng, C., Li, Z., & Huang, Y. (2015). Design and computation of coil inductance for induction cookers. *Russian Electrical Engineering*, *86*(2), 106-110.

[36] Omori, H., Yamashita, H., Nakaoka, M., &Maruhashi, T. (1985, June). A novel type induction-heating single-ended resonant inverter using new bipolar Darlington-Transistor. In *1985 IEEE Power Electronics Specialists Conference* (pp. 590-599). IEEE.

[37] El-Mashad, H. M., & Pan, Z. (2017). Application of induction heating in food processing and cooking. *Food Engineering Reviews*, *9*(2), 82-90.

[38] Byun, J. K., Choi, K., Roh, H. S., & Hahn, S. Y. (2000). Optimal design procedure for a practical induction heating cooker. *IEEE Transactions on Magnetics*, *36*(4), 1390-1393.

[39] Ryszard, N., &Marcin, W. (2011). Criterions for selection of volume induction heating parameters. In *Advances in Induction and Microwave Heating of Mineral and Organic Materials*. IntechOpen.

[40] Rudnev, V. (2004). A common misassumption in induction hardening. *Heat treating progress*, 23-25.

[41] Sweeney, M., Dols, J., Fortenbery, B., & Sharp, F. (2014). Induction cooking technology design and assessment. *Small*, *5*, 800.

[42] El-Mashad, H. M., & Pan, Z. (2017). Application of induction heating in food processing and cooking. *Food Engineering Reviews*, *9*(2), 82-90.

[43] Meyer, B. (2010). FERRITIC STAINLESS STEEL AISI 439 FOR THE SUGAR INDUSTRY. In *Proc. Int. Soc. Sugar Cane Technol* (Vol. 27).

[44] Matsushita, K., & Ishida, H. (1986). *U.S. Patent No. 4,614,852*. Washington, DC: U.S. Patent and Trademark Office.

[45] Pan, Z., &Atungulu, G. G. (2010). *Infrared heating for food and agricultural processing*. CRC Press.

[46] Fasina, O. (2003). Infrared heating of food and agricultural materials. In *2003 ASAE Annual Meeting* (p. 1). American Society of Agricultural and Biological Engineers.

[47] Riadh, M. H., Ahmad, S. A. B., Marhaban, M. H., &Soh, A. C. (2015). Infrared heating in food drying: An overview. *Drying Technology*, *33*(3), 322-335.

[48] Jun, S., Krishnamurthy, K., Irudayaraj, J., Demirci, A., Pan, Z., &Atungulu, G. G. (2010). Fundamentals and theory of infrared radiation. *Pan, Z., and Atungulu, GG (Eds.), Infrared Heating for Food and Agricultural Processing, CRC Press*, 1-18.

[49] Tomita, H., Maruyama, T., Yoshimura, S., & Takahashi, N. (2009, September). Superheated steam generator by induction heating. In *2009 13th European Conference on Power Electronics and Applications* (pp. 1-4). IEEE.

[50] Al-Shaikhli, A. K. M., &Meka, A. T. (2014). Design and implementation of practical induction heating cooker. *International Journal of soft computing and Engineering (IJSCE)*, *4*(4), 73-76.

[51] Stuchly, M. A., &Lecuyer, D. W. (1987). Electromagnetic fields around induction heating stoves. *Journal of microwave power and electromagnetic energy*, *22*(2), 63-69.

[52] Marbaix, J., Mille, N., Carrey, J., Soulantica, K., &Chaudret, B. (2021). Magnetically Induced Nanocatalysis for Intermittent Energy Storage: Review of the Current Status and Prospects. *Nanoparticles in Catalysis: Advances in Synthesis and Applications*, 307-329.

[53] Sastry, S. K., &Barach, J. T. (2000). Ohmic and inductive heating. *Journal of food science*, *65*, 42-46.

[54] TerMaten, E. J. W., &Melissen, J. B. M. (1992). Simulation of inductive heating. *IEEE transactions on magnetics*, *28*(2), 1287-1290.

[55] Gilchrist, R. K., Medal, R., Shorey, W. D., Hanselman, R. C., Parrott, J. C., & Taylor, C. B. (1957). Selective inductive heating of lymph nodes. *Annals of surgery*, *146*(4), 596.

[56] Ceylan, S., Coutable, L., Wegner, J., &Kirschning, A. (2011). Inductive heating with magnetic materials inside flow reactors. *Chemistry–A European Journal*, *17*(6), 1884-1893.

[57] Jordan, A., Wust, P., Fählin, H., John, W., Hinz, A., & Felix, R. (1993). Inductive heating of ferrimagnetic particles and magnetic fluids: physical evaluation of their potential for hyperthermia. *International journal of hyperthermia*, *9*(1), 51-68.

[58] Kirschning, A., Kupracz, L., &Hartwig, J. (2012). New synthetic opportunities in miniaturized flow reactors with inductive heating. *Chemistry letters*, *41*(6), 562-570.

[59] Kuznetsov, A. A., Shlyakhtin, O. A., Brusentsov, N. A., &Kuznetsov, O. A. (2002). Smart" mediators for self-controlled inductive heating. *Eur. Cells Mater*, *3*(2), 75-77.

[60] Lu, L., Zhang, S., Xu, J., He, H., & Zhao, X. (2017). Numerical study of titanium melting by high frequency inductive heating. *International journal of heat and mass transfer*, *108*, 2021-2028.