Application of Induction Heating in Food Processing and Cooking

Abstract Induction heating is an electromagnetic heating technology that has several advantages such as high safety, scalability, and high energy efficiency. It has been applied for a long time in metal processing, medical applications, and cooking. However, the application of this technology in food processing industry is still in its early stages. The objectives of this article were to review the basics of induction heating technology and the factors affecting its performance and to assess the application status of this technology in food processing. The research needs and future perspectives of this technology in food processing are also presented. Although several patents on using the induction heating to process food materials are available, there is still a need to generate more scientific data on the design, performance, and energy efficiency of the induction heating technology to be applied in different unit operations, such as drying, pasteurization, sterilization, and roasting, in food processing. It is needed to optimize different design and operational parameters, such as applied current frequency, type of equipment material, equipment size and configuration, and coil configurations. The information on the effect of the induction heating on sensory and nutritional quality of different food materials is lack. Research is also needed to compare the efficiency of the induction heating and other heating technologies, such as infrared, microwave, and ohmic heating, for food processing applications.

Keywords Induction food processing · Induction cooking · Energy efficiency · Alternative processing systems

Introduction

Induction heating is a non-contacting and complex process that combines electromagnetic, heat transfer, and metallurgical phenomena [1]. It has several advantages in temperature uniformity, high safety, maximum production rate, flexibility and compactness of heating system, quality assurance, process repeatability, automation capability, environmental friendless, reliability, energy efficiency, and cost competitiveness. It could be possible to achieve accurate and consistent heating using induction heating because it is possible to heat specific area on metal elements [2]. Induction heating can be explained by Faraday theory stating that a change in the magnetic environment across a conductor results in an electrical current that can be induced in that conductor [3].

Induction heating has gained strong interests in several industries, particularly in metal industry, glass and quartz processing, semi-conductor fabrication, and chemical synthesis of liquid and gases. It has been successfully used in both residential and commercial cooking where electromagnetic energy is converted into heat within the material of a cooking utensil [4]. Furthermore, it was applied in other applications including (1) production of saturated steam and superheated steam used for drying processes, sterilization, rinsing and cleaning, and soil purification [2] and (2) heating of the fast pyrolysis of agricultural wastes (i.e., rice husk and straw, coconut shell, and sugarcane bagasse) and sewage sludge from food processing plant [5, 6]. The state of art of induction heating systems was reviewed by Lucia et al. [7]. They presented main components of induction heating systems for industrial, medical, and domestic applications. They also presented the modulation and control algorithms applied to accurately control the power converter and the induction heating performance. They mentioned that although all applications of induction heating are based on the same fundamental principle, they exhibit differential characteristics and performances. While domestic application of induction heating in cookers requires low-cost configurations due to the limited cooling capabilities, industrial applications require well-designed cooling and control systems that could comply with the high output powers and reliability.

Despite the wide applications of the induction heating in many industries for many years, experimental data on the application of induction heating for food processing are extremely limited. The lack of scientific data and information on the design and performance of induction heating in different food processes has hindered the commercialization of the induction heating in food industry that is an energy-intensive industry. The objectives of this article were to review (1) the basic principles of induction heating systems and the factors affecting their performance and efficiency, (2) the applications of the induction heating in cooking and food processing, (3) the suitable materials for induction heating equipment and utensils, and (4) future prospective and research needs for the applications of induction heating in food industry.

Principles of Induction Heating

Induction heating system is composed of an induction coil, power supply, converters, and quenching system. The material to be heated, usually conductive and ferrous material, is placed in a fluctuating magnetic field. In metal processing, the material to be heated is called workpiece that is the product. In food processing and cooking, food material as a product is indirectly heated by conduction through a ferrous material. To differentiate from metal processing, in this review for food processing, we call the ferrous material as heatpiece. The electromagnetic field generates Foucault (eddy) currents in the workpiece/heatpiece, which induce Joule heating [8]. Figure 1 shows the main components of an induction heating system. The applied alternating current in an induction coil produces a time-variable magnetic field in its surroundings. The produced magnetic field has a similar frequency as the coil current. The strength of the magnetic field depends on the current applied in the induction coil, the coil geometry, and the distance from the coil. During heating, in addition to the eddy currents, heat can also be produced in magnetic materials due to the hysteresis effect. The latter is an internal friction created when magnetic parts pass through the inductor. The hysteresis effect does not occur at temperatures above the Curie point that is the temperature at which a material loses its magnetic properties [9]. Curie temperature depends on material type and its purity. Curie temperature for nickel ranges between 353 and 360 °C [10] and for iron is 770 °C [11].

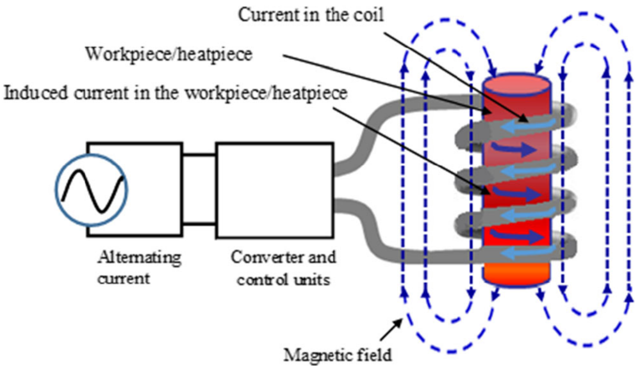
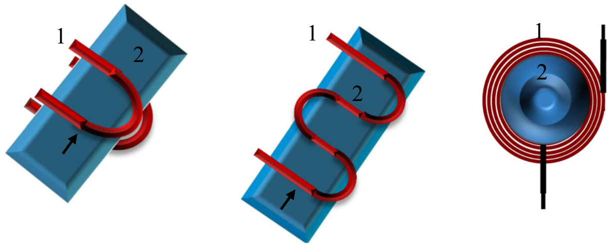


Fig. 1 Main components of induction heating systems (based on Rudnev et al. and Lucia et al. [4, 7])

Induction heating may be distinguished from microwave heating by the frequency and nature of heating source. While coils and magnets are needed for generation of the electromagnetic field in the induction heating, a magnetron is needed for microwave heating. Depending on the dimensions and the material properties of workpiece/heatpiece, most practical frequencies used for steel heating range from 60 Hz to 450 kHz [8]. Most of microwave magnetron generates microwave at a range of band 2450 ± 50 MHz [12]. Microwave energy could be absorbed directly by organic materials, but induction electromagnetic waves should be absorbed by metallic materials, and then indirectly heat organic materials via heat conduction. Exposing pointed and thin pieces of metals to microwave could result in arcing, a phenomenon that results from the rapid heating of the metals inside a microwave.

Depending on the flow mode of the workpiece inside the heating coils, induction mass heating could be carried out in different heating modes: static, progressive multistage, and continuous and oscillation heating [1]. Usually, induction coils are cooled either with air or water to keep the coils at low temperatures, and therefore, a low resistance for current flow could be attained [13].

The coil shape depends on the geometry of heatpiece/workpiece. Cylindrical and rectangular multiturn induction coils are usually employed in induction mass heating applications [1]. Zinn and Semiatin [14] presented several designs for multiturn coils for parts of various shapes such as round, rectangular, and formed; pancake; and internal and spiral-helical. The multiturn and helical-shaped coil (Fig. 1) is the most common one used in metal industry and can also be used in heating of pipes (e.g., heat exchangers) in food industry. There are other coil designs that are used for flat surfaces, such as a transverse field coil, a face inductor, and a flat spiral coil as shown in Fig. 2 [13, 15, 16].



Transverse field coil Face inductor coil Flat spiral coil

Fig. 2 Configuration of induction heating for heating of workpieces/heatpiece: *1*, coil; *2*, workpiece/heatpiece (adapted from Kolleck et al. and Frogner et al. [13, 15])

The majority of induction heating cooker uses spiral flat-type multiturn coils [17]. Induction cooker is composed of an electronic circuit that delivers high-frequency current to a coil of wire embedded in the cooking surface [18]. A typical induction cooker uses a copper coil that is placed underneath a cooking utensil. The important design parameters of the coil include geometry size, number of turns, and distribution of the iron cores [19]. The coil design substantially affects the induction cooker efficiency that is dependent on the compatibility of the cooking utensil with the induction heating electromagnetic waves. The coil is usually cooled using a fan embedded underneath it. Induction cooker contains also thermal management and control subsystems that should be carefully designed [20]. Byun et al. [21] presented an optimal design procedure for induction cooker using experimental modeling and practical power source simulation. The procedure was applied in designing a small induction heating cooker.

Factors Affecting the Performance of Induction Heating Systems

There are several factors affecting the efficiency and the economics of induction heating, such as frequency and intensity of induced current; physical characteristics, dimensions, and shape of workpiece/heatpiece; design configurations of inductor; and desirable temperature range [4, 8]. The heating time, proper selection of power source, and control system for induction heating depend strongly on resistance and reactance of charges [22]. The efficiency of induction heating is affected by the gap between the surface of heatpiece and coil; higher efficiency is obtained with smaller gaps [17]. The physical characteristics of the workpiece/heatpiece include electrical resistivity and magnetic permeability. The magnetic permeability of materials is strongly related to material type and composition, temperature, and intensity of magnetic field. For non-magnetic materials like copper or aluminum, the relative magnetic permeability is unity. Heat builds up quickly in high-resistance materials, such as steel, tin, and tungsten. Electrical resistivity increases with temperature; therefore, hot workpieces have high accessibility for induction heating than cold pieces [4].

During induction heating, the induced current in the workpiece/heatpiece is concentrated on its surface and the current density exponentially diminishes as it reaches the core of the material. This is called the skin effect. The skin depth (i.e., depth of penetration) is the depth at which the current is 0.368 (1/*e*) of its value at the surface of workpiece/heatpiece [8]. The density of the current from the surface could be calculated as follows [4]:

$$I = I_o e^{-y/\delta}.$$

where

I	Current intensity at depth y (A/m^2)
y	Distance from the surface of workpiece/heatpiece toward the core (m)
I_o	Current intensity at the surface of the workpiece/heatpiece (A/m^2)
δ	Penetration depth (m)

Figure 3 shows a relationship between current density and distance from workpiece surface for selected materials. The penetration depth of the current in the workpiece depends strongly on the material type (i.e., electrical resistivity and permeability of workpiece/heatpiece), applied power, and the current frequency [4]. Lower penetration depths are obtained at high current frequencies. The frequency commonly applied in hardening of thin wires and large rolls could reach 4000 kHz and line frequency (i.e., 50–60 Hz), respectively [23]. Induction cookers are usually operated at switching frequency between 25 and 50 kHz [24]. For non-ferrous materials with low resistivity, penetration is deep. Therefore, it is possible to use 50/60 Hz for most metal heating applications with diameters between 125 and 300 mm and even that frequency could be used for aluminum bars with a diameter of 50 mm [8]. Due to the increased intensity of the applied current near the surface of workpiece/heatpiece, approximately

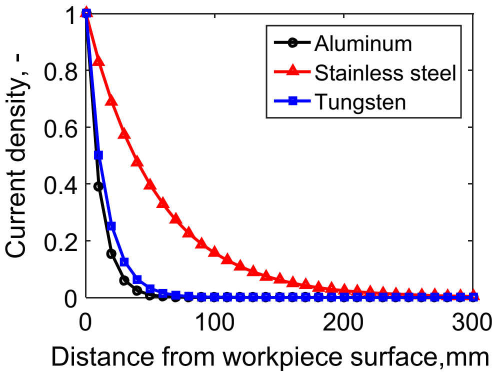


Fig. 3 Relationship between current density and distance from workpiece surface

86% of the power is concentrated at its surface layer [4]. Figure 4 shows the penetration depth of different materials at different frequencies. The penetration depth (δ, in m) was calculated based on the electrical resistivity and relative magnetic permeability using the equation presented by Rudnev et al. [4]:

$$\delta = 503000\sqrt{\frac{\rho}{\mu_r F}}$$

where

ρ Electrical resistivity of the workpiece/heatpiece (Ω m)
μ_r Relative magnetic permeability
F Current frequency (Hz)

Heat Transfer in Induction Heating and Material Selection for Heatpieces

Induction heating works only with conductive and ferrous materials. Depending on the material magnetic permeability and ferromagnetic properties, various metallic materials, such as steel, cast iron, among others, could be heated by induction [4]. To heat a non-ferrous material (e.g., food materials), a ferrous material should be used as a heatpiece. During heating, the heatpiece is heated by the induced current. Then, the heat is transferred to the processed food material via heat convection between the internal surface of heatpiece and the food material and heat conduction between different layers of the food material. For a non-ferrous container (e.g., glass, copper, aluminum, and non-magnetic alloys of stainless steel), an interface sheet made of ferrous metal is used as a heatpiece. The non-ferrous heatpiece is firstly heated by conduction of heat between it and the ferrous interface, and then, the food material is heated by convection and conduction as shown in Fig. 5.

Cookware and equipment contacting foods can be manufactured from either 304- or 316-type stainless steels because they are corrosion resistant and easy to clean using commercial cleaning methods such as steam- and water-assisted alkaline solutions and organic solvents. There are several stainless steel alloys, such as 444 stainless steel that is of low carbon and nitrogen and ferritic, which are currently used for food processing, hot-water tanks, and heat exchanger tubing. Stainless steel 444 is used in evaporator tubes, and stainless steel 410 is used in cane conveyors. Ferritic stainless steel type 410 was compared with the carbon steel at several sugar plants in Brazil [26]. It was reported that the ferritic stainless steel has several advantages: chemically and biologically inert that does not affect sugar taste or color and minimal risk of microorganism colony growth, minimal tendency for bacterial formation on the surface, no metallic migration to the end product, high corrosion and oxidation resistance, high abrasion resistance, higher thermal conductivity than type 304, easy to shape, and easy to wield in section thicknesses up to 30 mm. This stainless steel 410 had a reasonable initial investment costs and long life compared with type 304. It had also the best cost-benefit ratio compared to mild steel, austenitic stainless steel, and copper. Matsushita and Ishida [27] developed a cooking utensil for induction cookers. The developed utensil was made mainly of aluminum. The bottom of the vessel was coated by spraying a magnetic material, such as iron or cast iron. The coating material was covered with a non-magnetic layer made of aluminum. The developed vessel has several advantages, including corrosion resistance, high heating efficiency, lightweight, and good appearance.

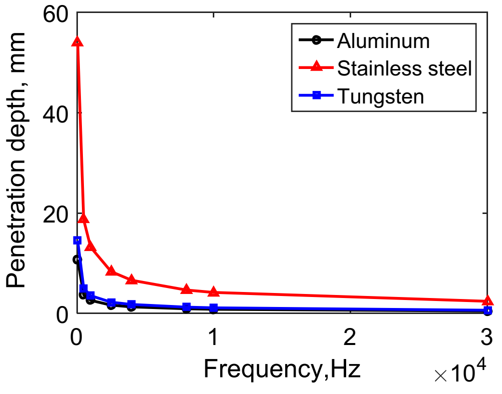


Fig. 4 Relationship between penetration depth and frequency

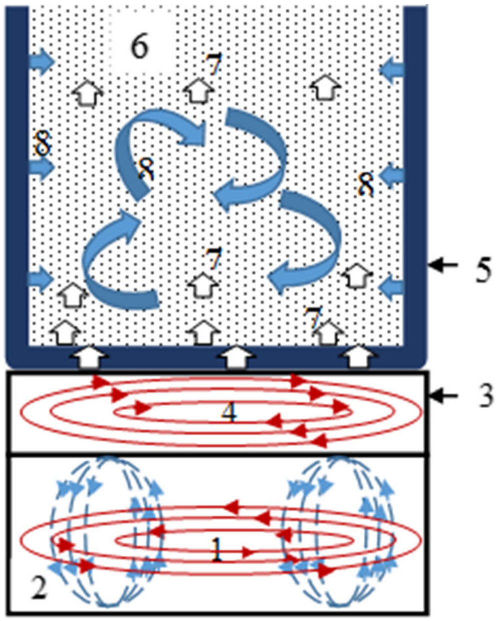


Fig. 5 A schematic of induction heating of a food material in a non-ferrous container (adapted from Onsemi [25]): *1*, coil and coil current; *2*, electrical magnetic field; *3*, ferrous interface (heatpiece); *4*, induced current; *5*, non-ferrous container; *6*, food material; *7*, conductive heat transfer; and *8*, convective heat transfer

Calculations of the Power Needed for Induction Heating

To calculate the required coil power (Q_c) during induction heating of a food material at the coil terminal (i.e., coil power), the theoretical thermal power needed to heat the heatpiece and food material to be processed to a specific temperature is divided by the electrical and thermal efficiencies (Rudnev et al. [4]):

$$Q_c = \frac{Q_{th}}{\xi_{el}\xi_{th}}$$

where

Q_{th}	Theoretical power needed (W)
ζ_{el}	Electrical efficiency, decimal
ζ_{th}	Thermal efficiency, decimal

Theoretical power needed is calculated by multiplying the mass of heatpiece and food material to be processed, corresponding specific heat of materials, and the temperature increase of each material:

$$Q_{th} = \frac{m_p Cp_p \Delta T_p + m_m Cp_m \Delta T_m}{t}$$

where

m_{p}	Mass of heatpiece (kg)
$\mathrm{Cp_p}$	Specific heat of heatpiece material (J/kg °C)
ΔT_{p}	Increase of the temperature of the heatpiece (°C)
M_{m}	Mass of food material (kg)
$\mathrm{Cp_m}$	Specific heat of food material (J/kg °C)
ΔT_{m}	Increase of the temperature of food material (°C)
t	Heating time (s)

The electrical efficiency is a function of the dimensions of the heatpiece, penetration depth in the workpiece and the heating coil, electrical resistivities of the coil and heatpiece, and the relative magnetic permeability of the heatpiece [4]:

$$\xi_{el} = \frac{Q_{th}}{Q_{th} + Q_{El\text{-loss}}}$$

where

$Q_{\mathrm{El\text{-}loss}}$	power loss in coil turns and power loses by conduction to the surrounding (W)

The thermal efficiency accounts for the thermal energy losses due to conduction, convection, and radiation during the heating process:

$$\xi_{th} = \frac{Q_{AV-th}}{Q_{AV-th} + Q_{Th-loss}}$$

where

$Q_{\mathrm{AV\text{-}th}}$	average heating power needed in a heating cycle (W)
$Q_{\mathrm{Th\text{-}loss}}$	power loss by conduction, convection, and radiation to the surrounding (W)

The average power needed to heat a material is used in calculating the thermal efficiency because of the variation of electrical resistivity and relative magnetic permeability over a heating cycle [4]. Thermal energy losses can be accurately determined using numerical computation or roughly using empirical formulas [28].

Applications of Induction Heating in Food Processing

Food processing is one of the most energy-demanding industries. Steam and hot air are the main and conventional heating sources for many food processes. However, due to the low-energy efficiencies of processes using steam, several other heating technologies, such as infrared, ohmic, and microwave heating, have gained a considerable research attention in recent years [29]. Induction heating could be a good alternative to the conventional heating technologies in food industry due to its advantages. Levacher et al. [30] mentioned that using induction heating for cooking flat products on a belt conveyor could save 50% of energy demand. Induction heating is a desirable heating source for evaporation processes for organic and inorganic liquids and could replace electrical furnaces with an energy saving of 20%. Induction evaporation has several features that make it more attractive than conventional heating [31]. It provides vapor ionization and high-density vapor plasma generation that help in obtaining high-quality coatings; it is used for evaporating chemically active, radioactive, and toxic substances and in vacuum and gas medium for the production of compound coatings and macroparticle and nanoparticle. The induction heating can be operated at high temperatures, up to 2000 °C, depending on the maximum operational temperature of evaporator materials. However, little information could be found in using induction heating in food evaporation.

In a US patent, induction heating system was designed and used to heat food materials [32]. The authors did not mention the type of the food material and the metal used for the equipment construction. The system was composed of a cylindrical metallic barrel that is rotated about an inclined longitudinal axis. Food materials are introduced into the higher end of the cylinder and are removed or discharged at the other or lower end. Induction coils circumferentially encircle the heating cylinder. Heat is induced throughout the wall of the cylinder and is then transmitted into the food material as the food material passes through. The heated cylinder was well insulated above the heating coil to minimize heat losses. Chavanaz and Losserand [33] developed a system for food heating using induction heating. The system consists of a series of trays arranged above each other. Food materials are placed on a part of the tray and covered under an insulating dish cover. Food tray included a layer of material that can be heated by magnetic induction. Induction shelves that comprise induction coils are inserted between the trays. The induction heating is switched on when dish covers are presented and are automatically detected when dishes enter the equipment.

An induction heating technology was patented to extend the life of frying oil during frying [34]. It was postulated that induction heating could supply electrons during frying, which creates an environment reducing the oxidation of oils. However, the exact physical or chemical mechanism for the anti-oxidation has yet to be discovered [35]. Wenstrup et al. [35] compared the patent of Maupin and Johnson [34] and conventional frying of French fries. Results showed that induction heating increased the time for oil utilization due to the reduction of the formation rate of free fatty acid (FFA) and aldehyde. FFA is an indicator for frying oil replacement [36]. Aldehyde is a source of off-flavor in fried products [35]. The authors mentioned that the induction heating system could be incorporated with existing frying equipment or built into new constructed ones.

Induction heating was also applied for the extraction of pectin from citrange albedos [37]. Extraction experiments were carried out using an induction plate, and samples were put in magnetizable and enameled containers. The time required for the extracting process was significantly shorter using induction heating (30 min) than conventional heating (90 min). Extraction using conventional heating was performed using a hot water bath. Pectin yield was higher using induction heating than conventional heating due to the interaction of electromagnetic fields and acidic and basic compounds in the material. Electromagnetic field caused agitation of ions and electrolyte compounds such as metal salts and galacturonic acid, which led to the temperature increase of aqueous solution.

Sadler [38] analyzed the performance of magnetic induction heat exchanger. The cross-sectional temperature distribution was evaluated using a 10-kW induction heater at 180 kHz. A heating efficiency of > 98% was achieved after including a heat exchanger unit to recover heat from the water used for coil cooling. Fairly uniform heating (within 4.7%) could occur in a centered six-tube bundle. However, non-uniformities could occur in heating along the heat exchanger. Atyhanov and Sagyndikova [39] proposed a grain dryer using induction heating. The drying system was consisted of a drying chamber around which induction coil is fixed. Grains were moved through the heated chamber under gravity force. Although the authors mentioned that the induction heating has several advantages such as high productivity, quality, and cost efficiency, no data were presented on the parameters affecting the performance and energy efficiency of the dryer. Tomita et al. [40] developed a superheated steam generator using induction heating. The generator used the cooling water of induction coil to convert it to steam in heated stainless steel disks using induction heating. The temperature of water after the coil and superheated steam could reach 100 and 300 °C, respectively. Although there is the presence of several patents on the application of induction heating in food processing, no information is available in the literature on the design and operational parameters and energy efficiency of induction heating systems for different food processes. There is also a dearth of information on the effect of the induction heating on the sensory quality and the functional compounds in different food materials. These are important areas for future research.

Induction Cookers

Induction cookers have been in the market for many years. These cookers have a higher energy efficiency and shorter cooking than electrical and gas stoves. They also possess high reliability, direct heating, high safety, low running cost, and non-acoustic noise [41]. However, Stuchly and Lecuyer [42] mentioned that short-time exposures to magnetic fields near induction stoves could cause detrimental health effect. No specific information was presented on the mechanism of the adverse effect of the induction heating on human health. General safety precautions for high voltage and hot surfaces should be followed. Vendors of induction cookers claim that the efficiency of induction cooker could reach 90%. However, Sweeney et al. [24] compared induction heating, gas, and electric cookers with exposed resistive coil cookers. Two vessel sizes with 15- and 24-cm diameters were used to compare the efficiency of the induction and conventional coil cookers. The studied heaters were used to heat 4.54 and 1.36 kg of water in the large and small vessels from 21 to 93 °C, respectively. The efficiency of cooking was calculated as the amount of energy gained by water divided by the total energy consumption by the cookers. Results showed that the efficiencies of conventional electric technology and induction heating large vessels were 83% and 77%, respectively. The contact area between the cookware and the heating media significantly affects the efficiency of the conventional coil cooker. The efficiency of conventional electric cooker was much lower for small cookware compared with the induction cookers that have relatively constant efficiency regardless of the size of the cookware (Table 1). The low efficiency of the conventional coil cooker was attributed to the radiation heat losses from the uncovered areas of the heating coil.

The Department of Energy [43] determined the efficiencies of several electric cookers covering a range of diameters and maximum rated power during heating different sizes of solid

Table 1 Cooking efficiency (%) of induction heating and conventional cookers

Cooker	Large vessel		Small vessel	
	Half power	Full power	Half power	Full power
Induction with a maximum power of 1500 W	74.9	77.6	76.5	77.4
Induction with a maximum power of 1800 W	75.9	77.2	75.6	75.1
Electric conventional coil	81.6	83.4	48.2	41.5
Natural gas[a]	41.7	35.2	–	30.2

Source: Sweeney et al. [24]

[a] Natural gas range was tested at 10 °C

aluminum test blocks (Table 2). Results showed that the measured efficiency during the heat-up period is generally higher for the induction surface units than other cookers. Induction heating had the shortest heat-up times than other heating technologies. For the same block size, decreasing the power and the surface diameter of induction cooker increases the heat-up time and decreases the heating efficiency.

We have experimentally determined the efficiency of a portable commercial induction cooker (Fagor America, Inc., NJ). The determined efficiency of the induction cooker was compared with that of a laboratory hot plate. Several experiments were carried out in duplicate. In each experiment, 500 ml of water was put in a 2000-ml glass beaker that had the dimensions of 186 × 130 mm (height × diameter). The third heating setting (127 °C) in the induction cooker was selected. The cooker was automatically switched off when the surface temperature reached a temperature close to the selected setting temperature. Then, it started heating again when the surface of the cooker reached a temperature of about 90 °C. The temperature of the cooker surface was measured using a non-contact IR thermometer (Lesman Instrument Company, USA). Circular stainless steel plates with the diameters of 130 and 110 mm were used as an interface between the induction cooker surface and the glass beaker. The circular plates were made of 430 stainless steel with the thickness 1.12 mm. Two experiments were also carried out to determine the efficiency of induction cooker using a 130-mm diameter and 0.6-cm-thick steel plate. The laboratory hot plate was set at the middle of the heating range. The initial temperature of water was measured using an alcohol thermometer. The temperature of water was measured and recorded periodically during heating process till the water temperature reached a temperature of 57–59 °C. The electrical energy consumption by the induction cooker was measured using a Wattmeter (Kill A Wattmeter ®, NY, USA).

The initial and final temperatures of water, heating time, and efficiency are shown in Table 3. Higher efficiency of the induction cooker and relatively short heating time were obtained with the stainless steel plate than the steel plate. This might be attributed to the differences in the thickness and material type of the plate that affect the rate of heat transferred by conduction from the interface plate to the glass beaker. The higher efficiency obtained with the 130-mm plate than the 110-mm stainless steel plate could be due to the small contact area between the beaker in case of the small size plate and/or the increased heat losses under long heating time (i.e., with 110-mm plate). The increased heat losses with the small plate could be caused by the low heat capacity and relatively long time needed for the cooker before starting the heating cycle again. There was no significant difference in the efficiency

Table 2 Cooking efficiency of induction heating and conventional cookers using heated aluminum blocks with different sizes

Test block size	Heating technology	Surface diameter (cm)	Maximum rated power (W)	Full test efficiency (%)	Heat-up efficiency (%)	Heat-up time (min)
27-cm test block	Induction	28	3700	78.18	77.34	6.33
	Smooth electric resistance	31	3000	72.95	66.12	8.97
	Induction	25	3400	69.79	67.48	8.00
23-cm test block	Induction	20	3200	73.78	68.20	5.05
	Coil electric resistance	20	2100	68.86	64.82	8.06
16-cm test block	Induction	15	1800	69.99	72.30	3.67
	Smooth electric resistance	15	1200	66.94	61.17	6.37
	Induction	18	2600	69.38	65.61	2.97
	Coil electric resistance	15	1250	73.54	70.60	5.43

Table 3 Comparison of the efficiency of a laboratory hot plate and an induction cooker

Heater	Heating interface	Initial temperature (°C)	Final Temperature (°C)	Time (min)	Energy (kWh)	Heat efficiency (%)
Induction	Stainless steel diameter 130 mm	27.5 ± 0.7	58 ± 1.4	6.37 ± 0	0.04 ± 0.01	51.84 ± 11.6
Induction	Stainless steel diameter 110 mm	26 ± 0.0	58 ± 0.0	20.5 ± 2.8	0.05 ± 0.0	37.21 ± 0.0
Induction	Steel (diameter 130 mm and thickness 0.6 cm)	24.8 ± 4	54.3 ± 0.4	24.45 ± 2.6	0.06 ± 0.0	28.6 ± 0.0
Hot plate	–	26.4 ± 0.7	54.4 ± 1.7	15.53 ± 5.4	0.03 ± 0.0	54.3 ± 1.1

between the induction cooker and the hot plate when using a 130-mm stainless steel plate. However, a significant reduction of heating time was obtained with the induction heating. The relatively lower efficiency determined in our experiments compared with those of Sweeney et al. [24] could be due to the differences in the heating vessels.

Conclusions and Future Research Needs

Induction heating is a fast, energy-efficient, safe, and scalable heating technology. It has been extensively applied in several fields such as metal processing, medical applications (e.g., sterilization of surgical instruments), biomass pyrolysis, and food cooking. A disadvantage of the induction heating is its limitation for heating non-ferric metals. However, using ferric materials as an interface between the induction heaters and the heating vessel could alleviate this hurdle. Lucia et al. [7] presented the future challenges of the induction heating. Among them are the improvement of semiconductor technology; development of multiple-output power converters that have flexibility, performance, and heat distribution; and development of advanced and robust control systems. They also mentioned that although the operational parameters of domestic and industrial application are well known, further research is still needed to optimize the performance parameters for the heating of low-resistivity materials and biological tissues for medical applications.

There are several patents on using the induction heating for food processing. However, only limited research is available on the designs and performance of food processing using induction heating. There is a need to optimize different designs and operational parameters such as applied current frequency, type of equipment material, equipment size and configurations, and coil configurations for different food processes, such as drying, pasteurization, sterilization, and roasting. Future studies are needed to investigate the effect of induction heating on the temperature profile and processing time of different food materials. There is also a dearth of information on the interaction between different food materials and the induced electromagnetic energy and the effect of the induction heating on sensory and nutritional quality of different food materials. Further research is required to determine the efficiency of the induction heating and compare it with other commercial heating technologies used in food industry. It is needed to evaluate the efficiency of smooth electric cooktops using both conventional and induction technologies [24]. The effect of induction heating on the kinetics and mechanism of microbial death is not known. Destruction kinetics of pathogens could be affected by the interaction between temperature and electromagnetic and electric fields [44]. There is little information in the literature about the effect of the induction heating on food safety. Future research is also needed to compare induction heating with other heating methods, such as ohmic heating, with respect to energy efficiency and food safety. The operational parameters of different food processes (e.g., drying, sterilization, pasteurization) need to be optimized for different equipment materials. This would lead to developing cost-effective materials that could be used with induction heating systems.

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