Aalto University
School of Chemical Engineering
Master's Programme in Advanced Energy Solutions - Industrial Energy Processes and Sustainability

Tarique Jhatial

Thermal Characterization of Electric Stoves

Master's Thesis
Espoo, August 12, 2021

Supervisors: Associate Professor Simo Hostikka, Aalto University
Advisor: Simo Hostikka

Aalto University
School of Chemical Engineering
Master's Programme in Advanced Energy Solutions - Industrial Energy Processes and Sustainability

ABSTRACT OF MASTER'S THESIS

Author:	Tarique Jhatial		
Title:			
Thermal Characterization of Electric Stoves			
Date:	August 12, 2021	**Pages:**	84
Major:	Advance Energy Solutions	**Code:**	CHEM3044
Supervisors:	Associate Professor Simo Hostikka		
Advisor:	Simo Hostikka		

Ignition risks associated with cooktops have increased despite the advancement in the cooktop technologies.The fires caused by cooktops cannot be completely avoided, but with significant research there can be potential decrease in kitchen fires incidents associated with cooktops. In this work, we try to improve our understanding of cooktop ignitions and the effects of the cooktop types on the ignition risk. A series of experiments were conducted to thermally characterize several types of electric cooktops which can be useful for assessing the cause for ignitions in future. Furthermore, the thermal responses of cooking pans of different materials are analyzed on heating elements of all three cooktop types.

Three commonly used cooktops were tested including an electric coil cooktop with cast iron plate, ceramic glass cooktop and an induction cooktop. The electric power and temperature of the heating element of cooktops were measured at different knob settings using power analyzer. Temperature at different parts of cooktops was measured by using thermocouple, and infrared camera. Additionally, radiant heat flux was measured for electric coil and ceramic glass cooktop by using heat flux sensor.

The results showed that the maximum surface temperature in electric coil and ceramic glass cooktop can reach to 620°C and 590°C respectively and can easily ignite different cooking oils and solid materials. In all three cooktops, within first few minutes, different frying pans (cast iron, carbon steel and aluminum) can reach to the ignition temperature of different cooking oils and solid substances. This study provides information to evaluate the competency of different types of electric cooktops in terms of igniting a variety of common kitchen items.

Keywords:	cooktop fires, fire growth, residential fires, ignition prevention, cooktop technology
Language:	English

Acknowledgements

This work was funded by the Finnish Fire Protection Fund (Palosuojelurahasto) under the 'Liesipalojen syttyminen, vaikutukset ja ehkäisy'-project.

I am very thankful to my supervisor and advisor, Associate Professor Simo Hostikka for his guidance and assistance for the successful completion of the experiments. I would specially like to thank Vadim Desyatnyk and Ari Kankkunen for providing their expertise and useful discussion whenever needed. I would also like to recognize the extraordinary assistance that I recieved from Ari Haavisto, particularly for the power measurements.

Espoo, August 12, 2021

Tarique Jhatial

Abbreviations and Acronyms

NFPA	National Fire Protection Association
US	United States
UK	United Kingdom
FEMA	Federal Emergency Management Association
FP	Flash Point
AIT	Auto Ignition Temperature
EC	Electric Coil
CG	Ceramic Glass
IC	Induction
CI	Cast Iron
CS	Carbon Steel
AL	Aluminum
IR	Infrared
TC	Thermocouple

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Background

Cooktops are integral part of kitchens and has been used for ages in every home. With advancement of technology, the use of stoves has also increased. By 19th century, both gas and electric stoves were introduced separately. However, the use of gas cooktops remained popular as compared to electric cooktops because of grid irregularities. The induction cooktops were invented in 20th century, but they did not get public attention that time. Now a days, above mentioned cooktops technologies are widely used around the world.

With increased use of cooktops, the potential risks for ignitions have also increased [1]. According to NFPA, during 2014-2018, the cooking was the leading cause for reported home fire and injuries.Furthermore, cooking also remained the second cause for deaths by home fire. An average of 172,900 home structure fires were caused by cooking in US. As a result of these fire, an average of 550 people died, and 4820 people injured annually.

Despite the improvements in cooktop technology, the number of fire incidents have increased. Cooktops are the cause of around 61% for kitchen fires. They accounted for 87% of deaths, and 78% of injuries by cooking fire. According to report by NFPA, the households with electric cooktops have higher risk of catching cooking fire.

According to the Finnish rescue service, nearly 1000 fires from cooking are recorded per year. In PRONTO data, 34% of the building fires caused by cooktops are originated from food or fat. Majority of the fires were caused by the unattended cooking. A survey from SPEK was conducted in 2021 and it showed that around 53% people used traditional electric coil cooktop with cast iron plate, whereas ceramic glass cooktop is used by 25% people when the fire accident occured. [2]

Now a days, the popularity of induction cooktops is increasing since there is no exposed hot surface being used, and many people believe that there is no fire hazard associated with induction cooktops. As compared to traditional cooktops, induction cooktops are energy efficient and posses enhanced safety features such as reduced risk of burning or ignition by spilled oil or no power output after removal of cookware from hob. However, there can be major three elements that might cause the fire threat; induction type cooktop itself, cookware, and cooking items such as cooking oil used for cooking. Therefore, inappropriate usage of any of these three elements may result in fire of induction cooker.

Despite the modern cooktop technologies, there is a subjective gap in the knowledge concerning the factors leading to cooktop fire. For instance, the development of stove guard technologies has led to the development of stove guard standard EN50615, which focuses solely on oil fires. How easily and in which condition do other materials ignite? And even before that, how does the cooktop temperature evolve over time, and how quickly can they ignite typical materials that may serve as the first ignition source? The fires caused by cooktops cannot be completely avoided, but with significant research there can be potential decrease in kitchen fires incidents associated with cooktops.

1.2 Cooking fire risk

A residential flat was destroyed by fire on 10th January, 2021 in Beckenham, UK. A fire was initiated in the kitchen due to pan oil was ignited on heating cooktop. As per reports, 40 peoples vacant the building prior to arrival of the fire brigade and reportedly there were no injuries in the incident. [3]

Another similar incident happened in Pennsylvania, USA on 27th April, 2018 in which one person died. A fire was initiated in the kitchen when an unattended food was left on the cooktop. [4]

In both cases, the main reason for the fire was unattended cooking. Also, there was not any automatic detection or suppression system installed in the kitchen/building that lead to fire expansion before any indication to occupants.

To avoid this situation in future, smoke detectors and suppression system should be installed in the kitchen adn rooms. When cooking with hot oil, an extra care should always be taken because it can very easily be overheated and catching fire.

1.3 Aims and objective

Considering the severity of fire injuries associated with cooktop fires, the effective way to avoid them is to prevent the occurrence of ignitions in the first place.The primary objective of this thesis is to understand and analyze the ignition risk associated to three different types of cooktops (an electric coil cooktop range with cast iron plate installed, ceramic-glass cooktop range, and induction cooktop). Furthermore, the thermal responses of cooking pans of different materials are analyzed on heating elements of all three cooktop types. The obtained thermal responses are compared with the ignition values of different cooking oils and food items reported in the literature.

Chapter 2

Electric Cooktops

2.1 Introduction

Cooktops are the equipments that make a very great inclusion to any kitchen, by providing a high-quality surface of cooking to prepare meals without directly using an oven beneath it. Among wide range of cooktops, electric cooktops are designed to represent the aspect and sense of conventional cooktops heating by using the electricity. Because a regular electrical output that can be movable is used to plugged in these types of cooktops, compared to other cooktops, such as gas and wood cooktops that require the installation at the specific location.

2.2 History of cooktops

Until the end of 18th century, people of Europe were still using the open flame cooking which had several potential risks such as excess smoke in confined area and physical danger. In 1790s, a kitchen range was invented by scientist Benjamin Thomson. It was made of several bricks with a cylindrical oven and provided with holes on top so that cooking vessels can be placed over it [5]. Though it was large for domestic use but by its introduction, a continuous development was started. By the mid of 1800s, the masonry was replaced by cast iron in these types of ranges. As a result, units became smaller and more portable [6].

The gas cooktops were invented in 1802 by Zachaus Winzler in Germany and by 1826 were patented in England [7]. However, they were not practically being used due to incompletion of pipelines that would supply the fuel. The pipelines were widely spread throughout the Europe and USA by

1880s [6]. The use of gas cooktops is still very common today.

In 1859, the first patent for electro-heater was presented by George B Simpson [8]. The metal surface of electro-heater was heated by platinum wire coil and batteries were used as power supply. In 1893, the Chicago Worlds Fair was organized where the first electric stove was demonstrated [6].

Due to grid irregularities, the electric stoves did not catch much attention. In beginning of 20th century, electricity became widely available in homes, and different alloys were discovered that increased the durability of heating elements. By 1930s, the manufacturing cost of the electric stoves decreased and being easy to operate, they started to compete the gas cooktops [6].

2.3 Operation principle and control

In general, electric stoves are equipped with thermostat, heating element with coil shape covered on top for cooking [9]. The standard electric cooktop is provided with two large heating surfaces and two small heating sufaces, which are associated with the fundamental part of the stove where the power is constrained by the dials on the head of the cooktop [10]. In these types of cooktops, an electric current is flowing through highly resistive coils to produce the heat and that heat is used for cooking [11]. Compared to gas stoves, electric stoves cannot be immediately heated up and cooled down [12]. Figure 2.1 shows the basic working principle of an electric cooktop.

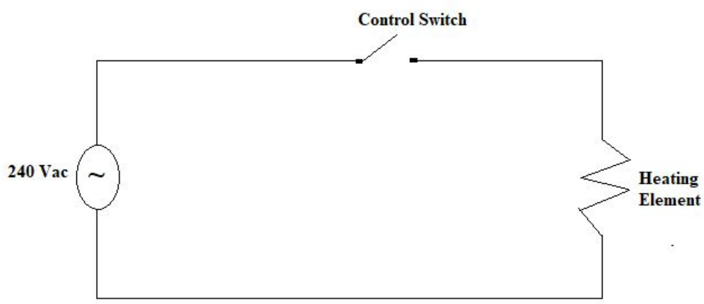


Figure 2.1: Schematic of electric cooktop

Each heating element on the top of electric cooktop is connected to its individual control switch. The cooktop is operated by utilizing the 240 volts of alternating current. By turning on the selector knob to heat setting, the switch enables the traveling of current through the circuit and the heating of element begins. The heating element is regulated by switch. When the heating element attains the selected temperature, the control switch is shut off that stops the flow of the current. This cycle is repeated throughout the process of cooking to sustain the appropriate temperature. [9]

An electrical energy is converted into heat energy by using the heating element in different types of conventional electric ranges, ovens, and cooktops. Whereas in conventional ranges and cooktops, there is direct contact between bottom of pot or pan and heating element, so the heat is transferred through conduction between two surfaces [12].

The outlook of an induction cooktop is also similar to other electric ceramic cooktops with various sizes of heating zones for cookwares. An induction cooktop as shown in Figure 2.2 [13] is consisting of ceramic glass plate with heat resistant properties on which the cookwares are placed for the heating. An electromagnetic coil of metal is placed exactly beneath the plate and it is electronically controlled. This coil is responsible for the heating of the pots and pans.

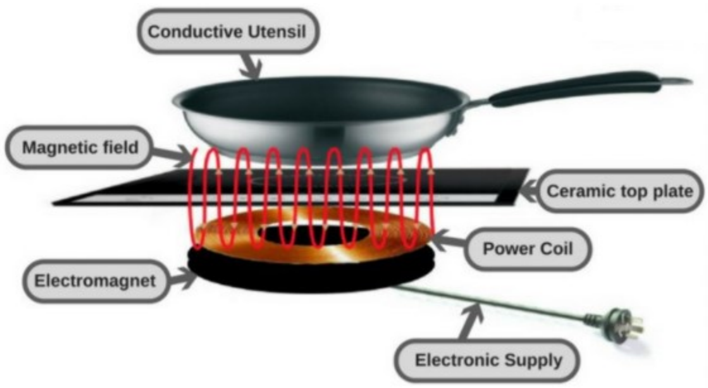


Figure 2.2: Contruction and operation of induction cooktop

When the cooktops power supply is switched on, the passage of an electric current through the coil is started [14]. Around the coil, a magnetic field is produced in certain direction when an electric current is started passing through the coil. However, there is no generation of heat until this point. The induced magnetic field in the coil starts to penetrate to the surface of cookware made of suitable material such as iron is placed over the cooktop. The flow of an electric current is started across the surface of pan due to fluctuating magnetic field. Therefore, an eddy current is induced in the cookware. The energy in form of heat is dissipated when this induced current is passing through the the cookware. As a result, the temperature of the cookware raises and food inside the cookware is cooked by transfer of heat (conduction and convection). The switching frequency for the induction cooktops ranges between 25 KHz and 50 KHz [14].

2.4 Electric cooktops technologies

Below given are different technologies for electric cooktops:

1. Electric coil cooktop
2. Electric smooth top cooktop
3. Induction cooktop
4. Modular cooktop
5. Integrated cooktop (downdraft)

2.4.1 Electric Coil Cooktop

As shown in Figure 2.3 [15] ,these types of cooktops have spiral shaped surface for cooking. The coil is light up when the heating elements are ready. Coil cooktops usage are suitable for heavy cookware such as heavy cast iron pans since it may damage limited resilient cooktops [16]. To protect the electrical wiring, drip pans or bowls are provided beneath the burner in case of any kind of spills [17]. Cooktop surface and drip pans need to be cleaned actively because being tough but still after some time they might need to be replaced being so greasy or defected to operate.

Figure 2.3: Electric coil cooktop with cast iron plate

2.4.2 Electric smooth top cooktop

As compared with coil type cooktop, a smooth surface without cracks or crevices is used in electric smooth top cooktops which enable it to overcome the spilled food issue that can hide in coil type cooktop [16]. The advantage of smooth surface is that it is easy to clean after cooking. Cooking top surface is manufactured of ceramic glass that features glistening and modern. An extra care is required while cleaning of smooth top cooktop, because using the wrong type of cookware on its surface may cause scratches or damages [17]. Also, if something is burnt over the cooktop surface then it might be hard to remove. Below given Figure 2.4 [18] shows the smooth top cooktop.

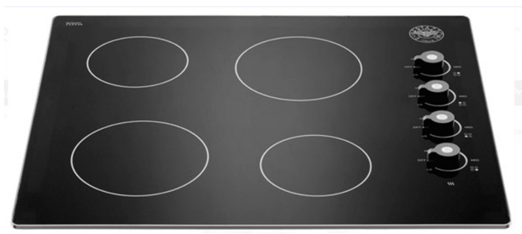


Figure 2.4: Electric smooth top cooktop

2.4.3 Induction cooktop

In induction cooktops, an electromagnetic energy is utilized to cook the food [17]. Under the cooking surface electromagnets are installed and when stove is plugged on to an electricity,currents are generated in the ferromagnetic metal due to the alternating electromagnetic wave, and current going through a resisting material generates heat [16]. As shown in Figure 2.5 [19], for induction cooktop, cookware with steel, iron or magnetic stainless-steel bottoms are used.

Figure 2.5: Induction cooktop

It is assumed that the induction cooktops reduce the risk of kitchen fire because of absence of open flame or heated surface as they only produce heat when cookware is placed over its surface. Also, compared with other cooktops, induction cooktop can attain the highest temperature in less time resulting in reduced cooking time. [16]

2.4.4 Modular cooktop

Both electric and gas cooking are combined in modular cooktop. As shown in Figure 2.6 [20], both gas and electric type burners are installed on the stoves surface. The benefit of this type cooktop is that it has ultimate cooking flexibility [17].

Figure 2.6: Modular cooktop

2.4.5 Integrated cooktop (downdraft)

Majority of the cooktops have an overhead hood to suck to steam and smoke from the pots and pans. In downdraft cooktop (Figure 2.7 [21]), there is small vent either along cooktops back or between the heating surfaces that will draw the heat and smoke during cooking and prevent it for reaching the ceiling [16]. An exhaust fan is situated within the cooktop or at the center of surface. This type of cooktop is suitable for the kitchens that do not have enough space for an overhead hood. However, ventilation system of downdraft cooktop is less efficient as compared to other traditional overhead hoods [17].

Figure 2.7: Downdraft cooktop

Chapter 3

Kitchen Fires

3.1 Statistics in USA and Europe

Cooking is a very common routine work that is easily forgettable and in result high temperature can easily lead to ignition. According to NFPA, cooking was the foremost cause for the domestic fires incidents and injuries and second most reason for the home fire deaths during 2014-2018 in USA. Every year, an average of 172,900 home structure fires are reported just in US. As a result of these fires, an average of 550 people died and 4820 people got injured annually. Ranges or cooktops were leading reason for 61% of reported domestic cooking fires, 87% of deaths by cooking fire and 78% cooking fire injuries. [1]

The data in Figure 3.1 [1] shows that there was decline in cooking fire from 1981. A slight increase in fire incidents can be seen in 1990s. The reported cooking fires remained maximum during year 2012-2015. The fire incidents decreased slightly in 2016 to 2018 but still they are historically high.

Figure 3.2 [1] shows the deaths caused by home cooking fire incidents from 1980-2018. The deaths remained high in 2014-2018 than in 1980-1984, despite that there has been very significant decrease in deaths during earlier period.

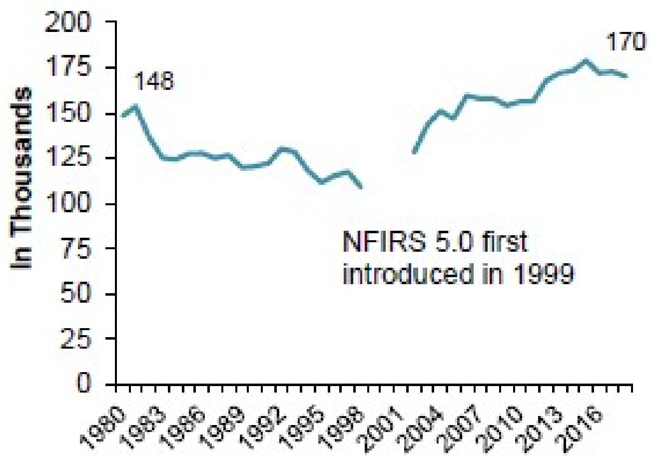


Figure 3.1: Reported home cooking fire incidents in USA from 1980-2018

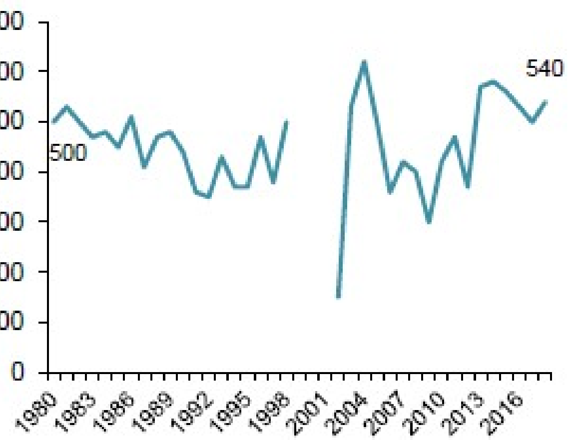


Figure 3.2: Reported deaths by cooking fire in USA from 1980-2018

As shown in Figure 3.3 [1], the injuries remained higher in 1980-1984 than in 2014-2018. However, there has been continuously decrease in injuries from 2012 to onwards.

Figure 3.4 [1] compares the home and cooking fire death rates between years 1980-1984 and 2014-2018. There has been around 49% decrease in home fire deaths in those time periods whereas 10% increase is reported in cooking fire deaths. In USA, cooking remained the root cause of home fires and injuries and the second leading reason for domestic fire deaths.

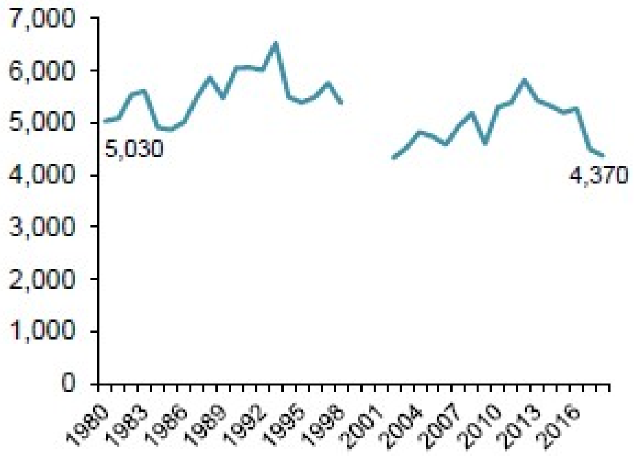


Figure 3.3: Reported injuries by cooking fire in USA from 1980-2018

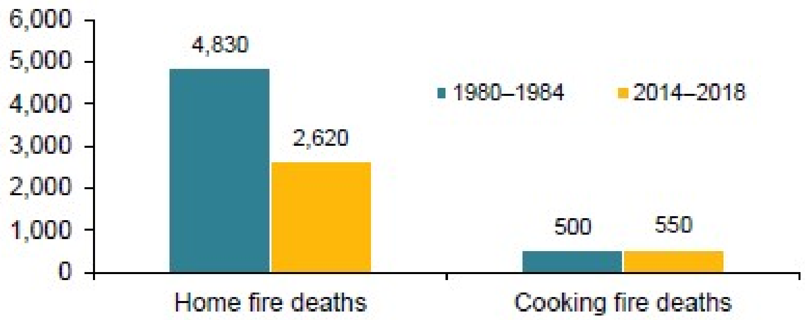


Figure 3.4: Average home and cooking fire deaths in USA

In all European countries, cooking is considered as a common cause of fire. However, cooking fire is rarely fatal. Figure 3.5 [22] illustrates the percentage of fatal fires in European countries because of cooking. It indicates that cooking is often the reason for residential fire but it does not lead to fatal fire. For example, an average of 15% fatal fire is caused by cooking in the Netherlands. In contrary, only 0.2% of fatal fire was caused by cooking in the UK. From 2010-2016, Finland reported 8% fatal fires originating from the cooking. Overall, cooking has remained common cause of fire in most of countries, but it has a low risk to have fatalities by fire.

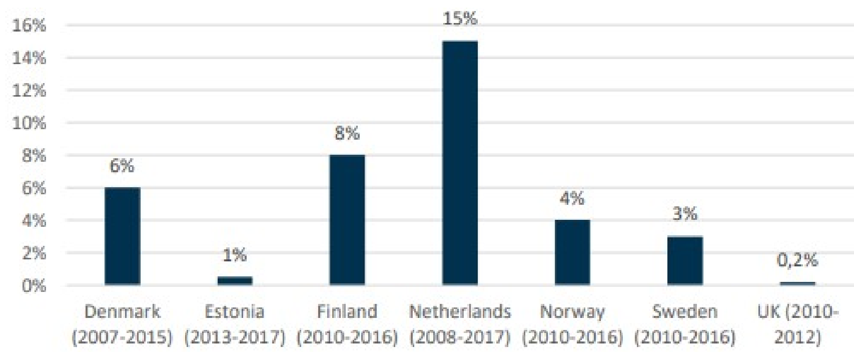


Figure 3.5: Percentage of fatal fires caused by cooking in European countries

3.2 Global Share of different cooktops

Figure 3.6 [23] illustrates the US market share of different cooking appliances in 2018. Gas cooktops with 38% are the leading cooking appliances used around the world followed by electric cooktops with 34%. Whereas, induction cooktops are used by 22% around the globe.

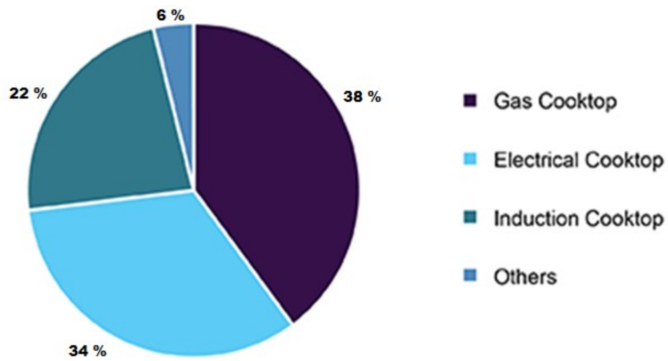


Figure 3.6: Household cooking appliance market share in US 2018

3.3 First material ignited in kitchen fire

According to the report by Federal Emergency Management Agency (FEMA) in 2005, the first common material ignited during the hob fire is the cooking material. Around 66% of domestic cooking fires are initiated with the cooking material ignition, including food. In half of the home cooking fires, cooking oil, grease, fat, and related substance were firstly ignited. The fire by cooking material or food originating from cooking oil or grease caused

58% of civilian deaths and 76% of civilian injuries and 77% direct property damage in USA [24].

3.4 Common ignition sources for cooking fire

Figure 3.7 [1] shows the common ignition sources for home cooking fire. According to NFPA, the cooktops are the serious threat for home cooking fires. Between period of 2011-2015, 62% of fires were caused by cooktops followed by oven or rotisserie with 13% fires. Cooktops fires resulted in 87% of deaths and 80% injuries.

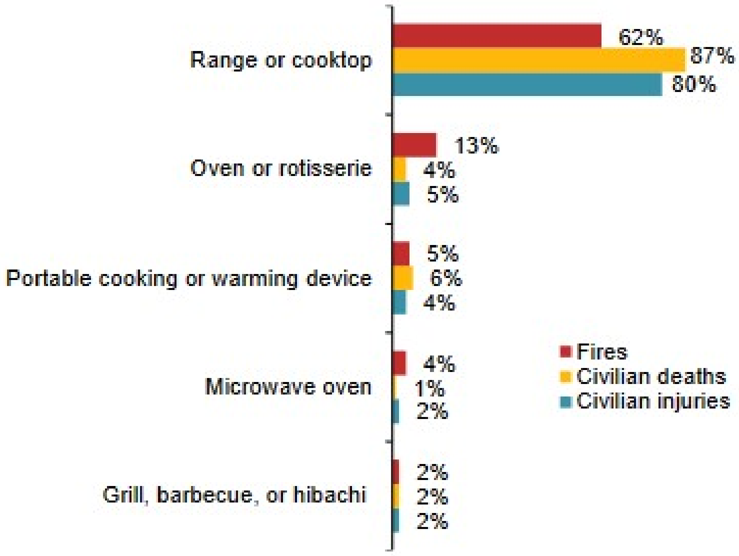


Figure 3.7: Home cooking fire common ignition sources 2011-2015

3.5 Causes of cooking fire

As shown in Figure 3.8 [1], the leading cause for the cooking fire is unattended equipment (31%) followed by abandoned or discarded material with 10%. However, heat source closed to combustibles and materials misuse are accounted for 9% of cooking fire. Both accidentally turned on and cleaning also cause 8% cooking fire.

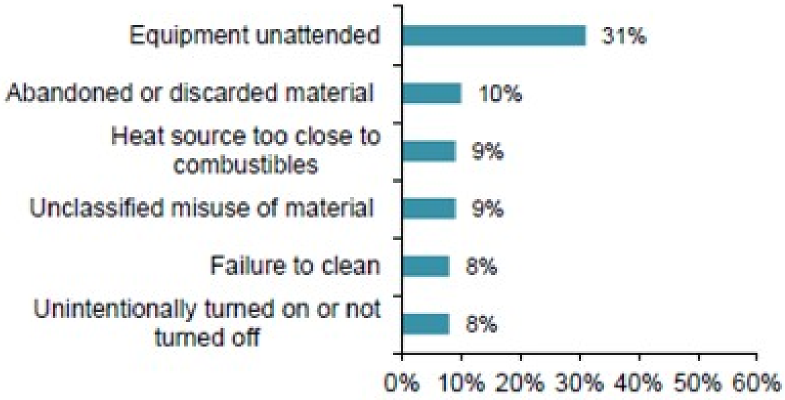


Figure 3.8: Home cooking fire causes 2014-2018

3.6 Kitchen fire prevention technologies

Generally, kitchen fire technologies are classified into two main categories; design technologies and fire protection technologies. Design technologies are referred to actual apparatus, and aspect of design that can prevent fires, decrease the probability of fires, and restrain severity and expansion of fire. From design technologies point of view, simple modifications are made in existing kitchens, such as designing type of ranges that automatically shut off when there is excess heat detected. Prevention technologies are referred to actual apparatus, and aspect of design that can prevent fires, decrease the probability of fires, and restrain severity and expansion of fire. From design technologies point of view, simple modifications are made in existing kitchens, such as designing type of ranges that automatically shut off when there is excess heat detected. [25]

3.6.1 Stove guards

Stove guards are used to protect the people and their property effectively from overheating of stoves. In some basic models, when temperature of stove is rising too high and rapidly, the stove guard cuts off the power. However, different type of stove guards are provided with the fire extinguishing system. The stove guards are provided with the temperature sensor above the stove. The power will be cut off by power management unit if the temperature increases rapidly. If the model is provided with extinguishing fire, then extinguishing liquid tank is above the extractor hood is installed. [26]

In March 2015, the new European stove guard standards EN 50615 were announced by the European Committee for Electrotechnical Standardization [27]. The purpose for EN 50615 was to identify the safety of cooking products effectively. There are three types of stove guards according to standard EN 50615:2015 [28]

1. **Type A:** In this type, when fire is started, an alerting sound is made. The extinguisher is activated within 30 seconds of fire and extinguish the fire with 15 seconds.
2. **Type B:** Before even start of fire the power is cut off and a loud fire alarm is continuously emitted until it is switched off or the temperature is dropped.
3. **Type AB:** In this category, before start of fire the power is cut off. In case fire starts, it will be put off by extinguisher.

Chapter 4

Ignition Theory

4.1 Ignition

The process in which external energy is provided to start the combustion is called ignition. During the ignition process, the exothermic reaction takes place and fuel undergoes thermolysis, i.e thermal decomposition of polymers (solids and liquids). There are two basic ignition types namely spontaneous (auto) and piloted. In pilot ignition, the flaming of flammable vapors/air is started by using electric spark plug or independent flame. Whereas in spontaneous, flaming takes place within mixture due to the heat of mixture. [29]

4.2 Ignition of liquids

To understand the ignition process of liquids, the elemental Physics behind the vaporization process of liquids should be analyzed. The evaporated vapors from the combustible liquid surface are flammable at high concentration. It possess identical nature and characteristics to the ordinary flammable gases.

Vapors cannot be ignited when their concentration above liquids surface is below the lower limit of flammability and flame will not propagate across vapor air mixture, and burning of liquid would not take place [30]. The lowest temperature at which vapors can ignite is known as flashpoint and combustible liquids are classified with respect to their flashpoints [31].

There are two methods for the measurement of flash point of the liquids [32].

1. Closed cup flash point measurement

2. Open cup flash point measurement

In general, flashpoints of liquids measured by open cup test are greater than closed cup. However, if the temperature of the vapors in an open cup test is greater than firepoint then the ignition of vapors will lead to sustained burning of the liquid. Firepoint is described as the lowest temperature at which ignition of the vapors is followed by the self-sustaining diffusion flame [33]. The measured values of open cup flashpoint and firepoints for different liquids are given in Table 4.1 [30].

Table 4.1: Some values of closed cup flashpoint, open cup flashpoint, and firepoint temperatures

Fuel Type	**Closed Cup FP (°C)**	**Open cup FP (°C)**	**Firepoint (°C)**
Methanol	12	1.0, 13.5	1.0, 13.5
Ethanol	13	6, 18	6, 18
s-Butanol	24	NA	29
n-Butanol	29	36	36, 38.5
Glycerol	160	176	207
Motor oil	216	NA	224

The table 4.2 [34] shows the fire point temperature for various types of cooking oils. When the oils continuously begin to smoke is termed as smoke point [35]. Smoke point is very important in cooking oils because if the temperature of oil exceeds the smoke point, it would start to burn or get a burned flavor.

Table 4.2: Fire point of different cooking oils

Substance	**Fire point Temperature (°C)**
Canola Oil	355 to 367
Soyabean oil	367
Corn oil	362 to 382

4.3 Ignition of solids

When external energy source is applied to solid materials at atmospheric temperature, then the materials exposed surface temperature begin to increase. As the energy is reached to the surface of material, several chemical and physical phenomena are started. There are different processes involved in ignition of solids.

In solid phase, by supplement of external energy source, the surface temperature of the material is increased. The maximum temperature would be achieved near to the surface, but there will be an increase of temperature in significant part of the material due to in-depth transfer of the energy. Therefore, the distribution of temperature varies with both depth and time, hence temperature is represented as a function of both variables [30].

In second stage, pyrolysis process takes place in which solid fuel is converted into the gaseous fuel and principally involves the molecules breakdown into various smaller molecules [36]. Pyrolysis is an endothermic process comprised of many chemical reactions that are strongly based on the temperature. Arrhenius type temperature functions are used to describe most of the pyrolysis reactions [30].

Once the process of pyrolysis is completed, gas is emerged above surface of the fuel. In the beginning, it is in lesser quantity but with increase in temperature and reaction depth, the mass flux of heat will increase. After that, emerging fuel will be encountered to the ambient oxidizer and in a result, flammable mixture will be produced. A flammable mixture is defined as the gas-air mixture that is able of being ignited by an open flame or device operating at or above the ignition temperature of the gas-air mixture[29].

When the flammable mixture is obtained, the temperature of the mixture is needed to be increased before occurrence of the combustion reaction. There is no external source of heat provided in auto-ignition for the initialization of the reaction, thus, to reach ignition point mixture needed to have absorb the adequate energy. To start the ignition process, the required amount of energy can be correlated by a Damkohler number [30]. This number correlates the ratio among local residence and chemical time. The measure of the reactants time they remain together is termed as residence time. While the necessary time required for the occurrence of reaction chemistry is called chemical time. The auto-ignition process is very complicated, and it involves the fully interlinking of solid and gas phases. Auto ignition data is usually recorded as auto ignition temperature (AIT) which refers to a temperature recorded when the first-time observation of flame ignition is made [37].The Table 4.3 shows auto ignition temperature for various types of solid substances.

Table 4.3: Auto ignition temperatures of different solid substances

Substance	**AIT (°C)**
Polymethyl methacrylate (PMMA) [30]	380
Polypropylene [38]	388
Cardboard [39]	427
Paper towel [40]	233

It is very difficult to characterize the auto-ignition process in a quantitative manner. Therefore, the pilot flame is introduced to simplify ignition process. In pilot ignition, when the external energy source causes a pyrolysis process and gases are emerged on the solid surface, then a combustion of the gas is initiated by introducing a flame, spark, or glowing wire [41]. Once the ignition is started and igniter is removed, the solid fuel will remain burning if the heat response to the surface of solid is sufficient for generation of combustible volatiles at a mass flux that will continue the flaming combustion [29].

Chapter 5

Materials and methods

5.1 Cooktops

Three different types of cooktop (Figure 5.1) were tested including an electric coil cooktop with cast iron plate, a ceramic glass cooktop and an induction cooktop.

The model number for electric coil and ceramic glass cooktop is RKL5100 and RHRN642X. Both cooktops are manufactured by Rosenlew. An induction cooktop is manufactured by Electrolux and has a model number HOI620S. Table 5.1 compares the different features of all three cooktops. In all three cooktops, left front burner was used for the experiments.

(a) Electric coil cooktop (b) Ceramic glass cooktop (c) Induction cooktop

Figure 5.1: Three different types of cooktops

Table 5.1: Comparing features of different cooktops

	Electric Coil	**Ceramic Glass**	**Induction**
Number of burners	4	4	4
Left rear burner diameter/power	145 mm / 1000 W	145 mm / 1200 W	145 mm / 1200W
Right rear burner diameter/power	180 mm / 1500 W	180 mm / 1800 W	180 mm/1800 W
Left front burner diameter/power	180 mm / 2000 W	120 mm / 210 mm / 750 W / 2200 W	210 mm / 2300-2800 W
Right front burner diameter/power	145 mm / 1500 W	145 mm / 1200 W	145 mm / 1200-1800 W
Product weight	40 Kg	7.4 Kg	10.8 Kg
Product dimensions (W X L)	500 mm X 500 mm	570 mm X 506 mm	590 mm X 520 mm
Controls	Rotary	Touch screen	Touch screen

5.2 Frying Pans

Frying pans made of three different materials; cast iron, carbon steel and aluminum are used as shown in Figure 5.2. Considering the fact that, aluminum pan is not purely made of just aluminum but it has small composition of different materials such as iron, an additional tests with different brand of aluminum pan were done. Specifications for different pans are shown in Table 5.2.

Sometimes, people put oven tray (Figure 5.3) directly over the cooktop surface to heat the food items such as pizza. Keeping this in mind, oven tray was also analyzed thermally with each cooktop.

Table 5.2: Comparing features of different frying pans

Type of pan	**Diameter (mm)**	**Weight (g)**	**Manufacturer**	**Brand**
Cast iron	280	1660	Opa	Kenno
Carbon steel	280	1330	Opa	Heavy Metal
Aluminum-A	280	850	Myhome kitchen	-
Aluminum-B	260	1135	Fiskar	Hard face

(a) Cast iron pan

(b) Carbon steel pan

(c) Aluminum pan-A

(d) Aluminum pan-B

Figure 5.2: Different types of frying pans

Figure 5.3: Oven tray

5.3 Instrumentation

This section describes the different types of instruments used in experiments. Figure 5.4 shows the schematic view of how different instruments were connected to each other.

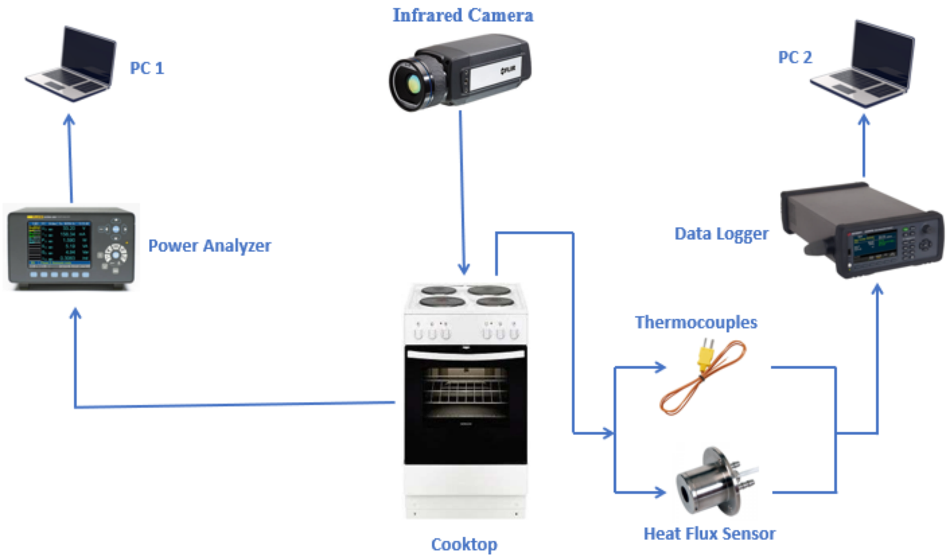


Figure 5.4: Schematic view of test setup

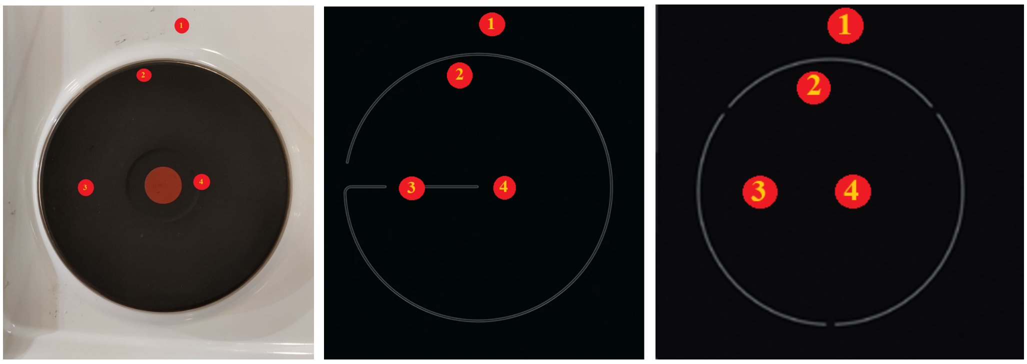
5.3.1 Thermocouple

Cooktop and pan surface temperatures were measured using K-type thermocouple. Table 5.3 shows the specifations for thermocouples used in the experiments.

Table 5.3: Specifications for thermocouple

Type	K
Temperature Range	-200 °C to 1250 °C
Wire size AWG Gauge	18
Wire diameter	1 mm
Standard Limit of Error	+/-2.2 °C or +/-2 %
Accuracy	+/-0.1 °C
Color coding	Yellow + , red -

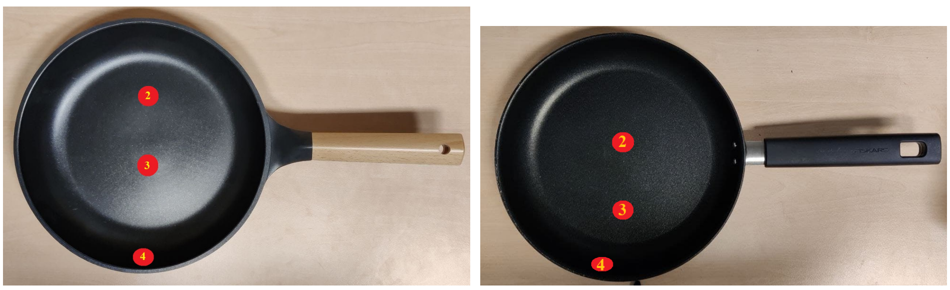
A systematic arrangement of four K-type nickel-chromium based thermocouples was used to measure the surface temperature of different cooktops and frying pans (Figure 5.5 & 5.6). Thermocouple T1 was placed beside the heating element surface, whereas thermocouples T2, T3, and T4 were placed directly against the heating element surface of each cooktop type. Light-weight concrete blocks of 20 cm^3 in volume and weight of 42 gram were used to ensure good contact between the thermocouple and the surface.



(a) Electric coil cooktop (b) Ceramic glass cooktop (c) Induction cooktop

Figure 5.5: Placement of thermocouples in each cooktops

(a) Cast iron pan (b) Carbon steel pan



(c) Aluminum pan-A (d) Aluminum pan-B

Figure 5.6: Placement of thermocouples in frying pans

With frying pans, thermocouple T1 remained at the same position and the other three thermocouples (T2, T3, T4) were placed against frying pan at different locations. An aluminum pan was provided with an iron inserted in its base to work with an induction cooktop.
Additionally, an oven tray was also analyzed thermally on all three cooktops. As shown in Figure 5.7, three thermocouples were placed against oven tray at different positions.

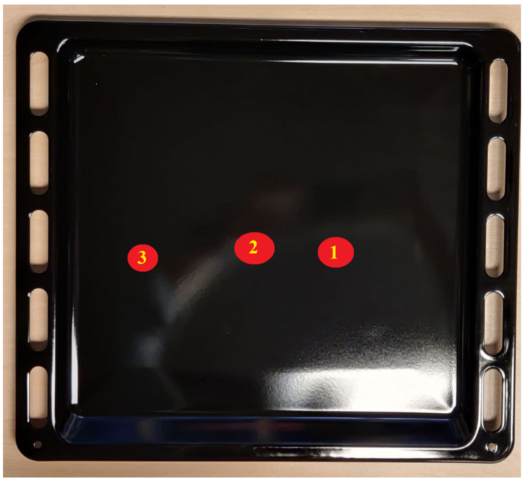


Figure 5.7: Placement of thermocouples in oven tray

5.3.2 Heat flux transducer

Hukseflux SBG01-050 sensor (Figure 5.8) is used to measure the heat flux. and it has following specifications shown in Table 5.4.

Figure 5.8: Hukseflux SBG01-050 sensor

Table 5.4: Specifications for heat flux sensor

Sensor manufacturer	Hukseflux
Sensor model	SBG01-050
Sensor type	Water cooled heat flux sensor
Output signal	DC voltage
Sensitivity	0.369 x 10^{-6} V/(W/m^2)
Measurement limit	Upto 50 x 10^3 W/m^2

As shown in Figure 5.9, the heat flux sensor is placed 30 mm above the heating surface. A tap water is used for the cooling of sensor.

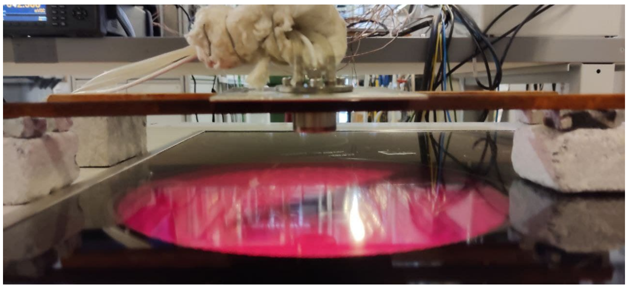


Figure 5.9: placement of heat flux sensor

5.3.3 Data acquisition system

Keysight DAQ970a data acquisition system (see Figure 5.10) is used to record the temperature measured by thermocouples. Systems accuracy of recording the temperature measured by thermocouple is 0.9 °C.

Figure 5.10: Keysight DAQ970a data acquisition system

5.3.4 Power analyzer

Fluke Norma 4000 power analyzer (see Figure 5.11) is used to measure the voltage, power output and current of different type of cooktops. Table 5.5 shows the specifications for power analyzer.

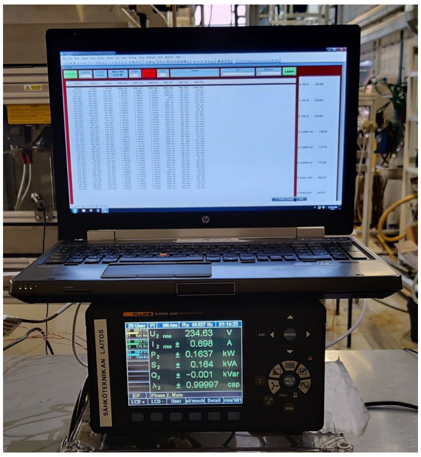


Figure 5.11: Fluke Norma 4000 power analyzer

Table 5.5: Specifications for power analyzer

Number of Phases	1 to 3
Weight	5 Kg
Size	150 x 237 x 315 mm
Basic Accuracy	0.2 %, 0.1 % or 0.03 %
Input Voltage Range	0.3 V to 1000 V
Input Current Range	0.03 mA to 20 A

5.3.5 Thermal infrared camera

To get the better view of spatial temperature distribution over the cooktop surface, a FLIR A655SC thermal camera (see Figure 5.12) is used along with the thermocouples. Thermal camera enables us to see the heat radiations emitted by the cooktop surface regardless of lighting conditions. Camera used for experiments have specifications shown in Table 5.6.

Figure 5.12: FLIR A655SC thermal infrared camera

Table 5.6: Specifications for thermal infrared camera

Detector Type	Uncooled Microbolometer
Resolution	640 x 480
Weight	0.9 kg
Size	0216 x 73 x 75 mm
Standard Range of Temperature	-40 °C to 150 °C , 100 °C to 650 °C
Optional Range of Temperature	Up to 2000 °C
Accuracy	+/-2 °C or +/-2 % of reading

Initially, emissivity of IR camera was set to standard value of 0.95. Due to reflective nature of ceramic glass cooktop, there was very large temperature difference between thermocouples and IR camera recorded values. By setting the the emissivity to 0.85, temperature difference was decreased considerably. In similar way, emissivity value was set to 0.97 in electric coil cooktop and different frying pans.

5.4 Experimental setup and process

All tests were conducted in Sahkomiehentie 4N at Aalto university. The experimental setup is shown in Figure 5.13. Three cooktop types were analyzed in terms of their surface temperatures; electric coil cooktop with cast iron plate, ceramic glass cooktop, and induction cooktop. Each test was repeated to all cooktops using different power settings of heating element. A systematic arrangement of thermocouples was used to record the temperatures of cooktops and pans. Power analyzer was used to measure the consumed power during each test. Meanwhile, each test was recorded by a thermal imaging camera.

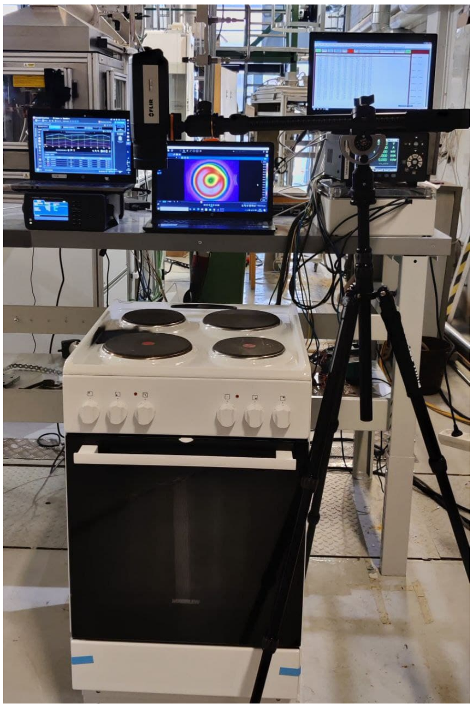
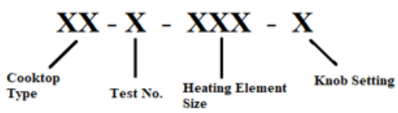


Figure 5.13: Experimental setup

5.5 Test matrix

All tests were performed to each type of cooktop. For each cooktop type, the heating element with highest power output was used for experiments. The surface temperature measurement tests were conducted only with electric coil and ceramic glass cooktop. For temperature measurement of all different cooktops, each test was repeated with different power setting. Whereas, for different frying pans on heating element, tests were conducted with medium and maximum power setting. The different acronyms used for the types of cooktop and pan include electric coil (EC), ceramic glass (CG),induction (IC), cast iron (CI), carbon steel (CS), aluminum (AL), oven tray (OT).



Tables 5.7 and 5.8 are providing a complete list of tests that are performed to electric coil cooktop with cast iron plate. Tables 5.9 and 5.10 are providing a

complete list of tests that are performed with ceramic glass cooktop. Table 5.11 is providing a complete list of tests that are performed with induction cooktop and Table 5.12 provides the list for heat flux tests.

Table 5.7: Electric coil cooktop test matrix

Test Matrix No.	1
Cooktop Type	EC
Test duration	60 min
Heating Surface Diameter	180 mm
Test Description	Temperature & power of cooktop surface
Test Id.	**Knob Position**
EC-1-180-1	1
EC-2-180-2	2
EC-3-180-3	3
EC-4-180-4	4
EC-5-180-5	5
EC-6-180-6	6
EC-7-180-6	6

Table 5.8: Electric coil cooktop with different pans test matrix

Test Matrix No.	2	
Cooktop Type	EC	
Test Duration	60 min	
Heating Surface Diameter	180 mm	
Test Description	Temperature & power with different pans	
Test Id.	**Pan Material**	**Knob position**
EC-1-180-3	CI	3
EC-2-180-6	CI	6
EC-3-180-3	CS	3
EC-4-180-6	CS	6
EC-5-180-3	AL-A	3
EC-6-180-6	AL-A	6
EC-7-180-6	AL-B	6
EC-7-180-6	OT	6

Table 5.9: Ceramic glass cooktop test matrix

Test Matrix No.	3
Cooktop Type	CG
Test duration	60 min
Heating Surface Diameter	210 mm
Test Description	Temperature & power of cooktop surface
Test Id.	**Knob Position**
CG-1-210-1	1
CG-2-210-2	2
CG-3-210-3	3
EC-4-210-4	4
EC-5-210-5	5
EC-6-210-6	6
EC-7-210-7	7
EC-8-210-8	8
EC-9-210-9	9
EC-10-210-9	9

Table 5.10: Ceramic glass cooktop with different pans test matrix

Test Matrix No.	4	
Cooktop Type	CG	
Test Duration	60 min	
Heating Surface Diameter	210 mm	
Test Description	Temperature & power with different pans	
Test Id.	**Pan Material**	**Knob Position**
CG-1-210-5	CI	5
CG-2-210-9	CI	9
CG-3-210-5	CS	5
CG-4-210-9	CS	9
CG-5-210-5	AL-A	5
CG-6-210-9	AL-A	9
CG-7-210-9	AL-B	9
CG-7-210-9	OT	9

Table 5.11: Induction cooktop with different pans test matrix

Test Matrix No.	5	
Cooktop Type	IC	
Test Duration	60 min	
Heating Surface Diameter	210 mm	
Test Description	Temperature & power with different pans	
Test Id.	**Pan Material**	**Knob Position**
IC-1-210-5	CI	5
IC-2-210-9	CI	9
IC-3-210-9	CI	Boost
IC-4-210-5	CS	5
IC-5-210-9	CS	9
IC-6-210-9	CS	Boost
IC-7-210-5	AL-A	5
IC-8-210-9	AL-A	9
IC-9-210-9	AL-A	Boost
IC-9-210-9	AL-B	9
IC-9-210-9	OT	9

Table 5.12: Heat flux test matrix

Test Matrix No.	6	
Cooktop Type	EC & CG	
Test Duration	60 min	
Heating Surface Diameter	180 mm & 210 mm	
Test Description	Heat flux in cooktops and carbon steel pan	
Test Id.	**Pan Material**	**Knob position**
EC-1-180-6	-	6
EC-2-210-9	-	9
EC-3-180-6	CS	6
EC-4-210-9	CS	9

Chapter 6

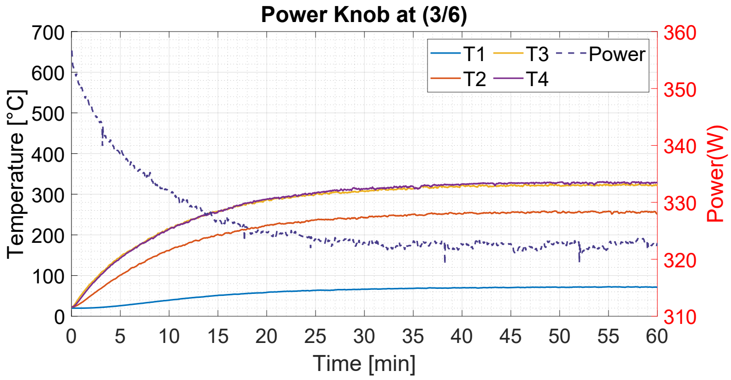
Results and Analysis

This chapter focuses the results obtained from each cooktop technology. In this section, only certain number of results are presented. However, supporting results can be found in the appendices.

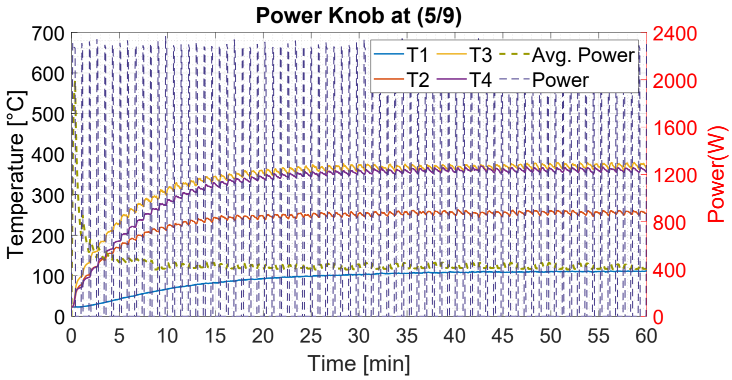
6.1 Temperature and power in cooktops

In this section, temperature in electric coil and ceramic glass cooktop are analyzed with respect to power. The first results in Figure 6.1 show temperatures and power consumption with the medium setting of power, i.e. (3/6) for the electric coil and (5/9) for the ceramic cooktop. These two cooktops show different trends of power: in the electric coil cooktop, the power decreases steadily from 360 to 325 W during the first 20 minutes, and then remains steady for the rest of the experiment. In ceramic glass cooktop, power switches on and off, with peak power of 2300 W and cycle duration of few seconds. The time averaged power of the ceramic glass cooktop was 400 W.

The surface temperatures measured from the two cooktops follows similar patterns. During the first 20 minutes, temperature increases continuously, reaching steady value in 40 min for the EC cooktop and 30 min for the CG cooktop. Ceramic glass cooktop shows relatively more fluctuation in temperature due to its power behavior.



(a) Electric coil cooktop

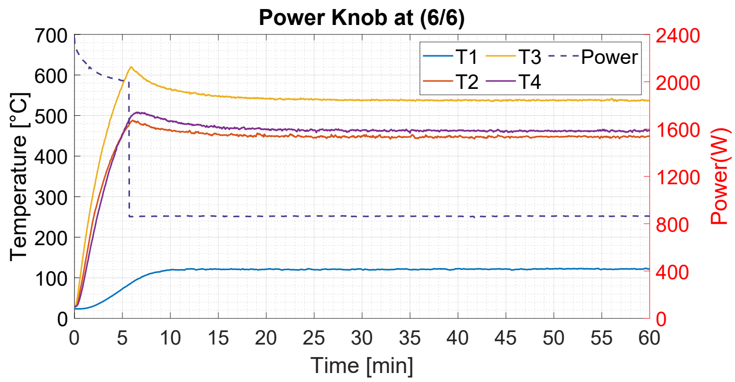


(b) Ceramic glass cooktop

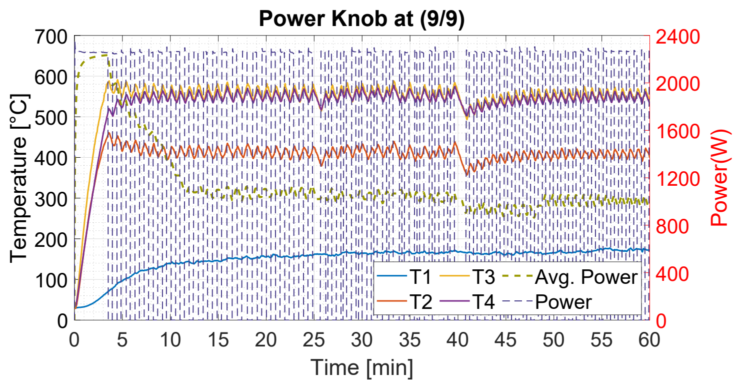
Figure 6.1: Temperature & power in EC & CG cooktop with medium setting

When an electric coil cooktop is at maximum power settings, then power abruptly increases to 2300 W and starts decreasing gradually to 2000 W during first 6 minutes (see Figure 6.2a). After 6 minutes, the power is cut off to capacity of 855 W for rest of the time. When power is maximum during first 6 minutes, temperature rises significantly, but as power is declined to 855 W, there is slight decrease in temperature for 10 minutes and then it remains constant for rest of time.

Figure 6.2b shows that by turning the ceramic glass on maximum power (9/9), the power remains at maximum value (2300 W) for four minutes, and then repeat the cyclic behavior with time averaged power of 1000 W. During the first four minutes, temperature increases rapidly then remains more or less constant with few tens of degrees fluctuation. More results for electric coil and ceramic glass cooktops with each power settings are provided in appendix A.



(a) Electric coil cooktop



(b) Ceramic glass cooktop

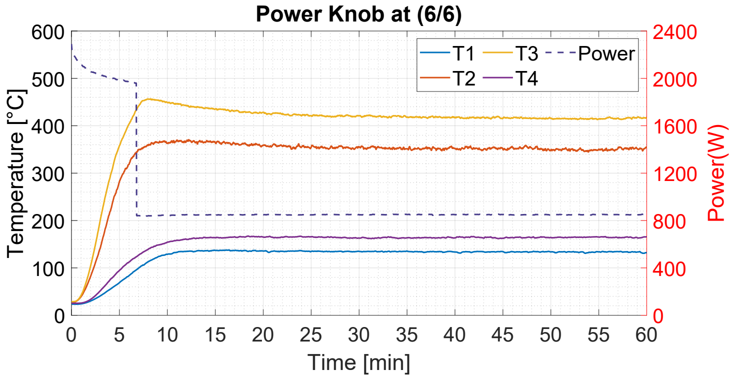
Figure 6.2: Temperature & power in EC & CG cooktop with full setting

6.2 Temperature and power in different pans

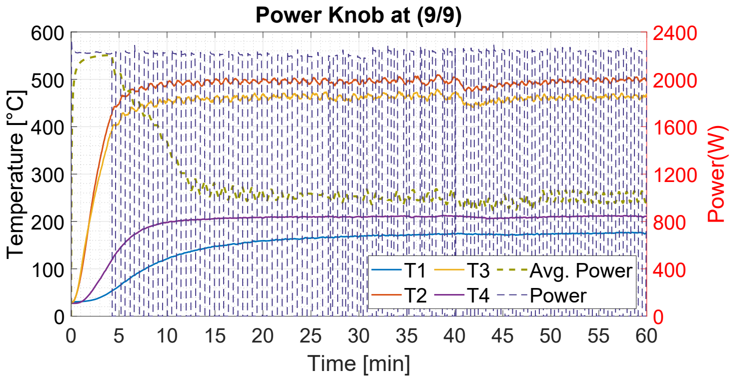
This section shows the results for temperature and power when frying pans made of different materials are placed on each cooktop at full power. Results for temperature and power for all three types of pans (cast iron, carbon steel & aluminum) with medium power settings are provided in appendix B.

6.2.1 Cast iron pan

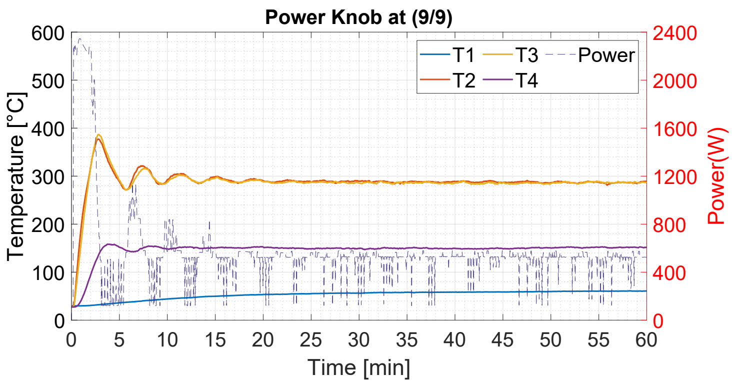
When cast iron pan is placed over electric coil and ceramic glass cooktop (see Figure 6.3 a & b), behavior of power follows similar pattern as it was without any pans in both cooktops.However, an operation principle of induction cooktop is dependent on the type of pan material used.



(a) Electric coil cooktop



(b) Ceramic glass cooktop



(c) Induction cooktop

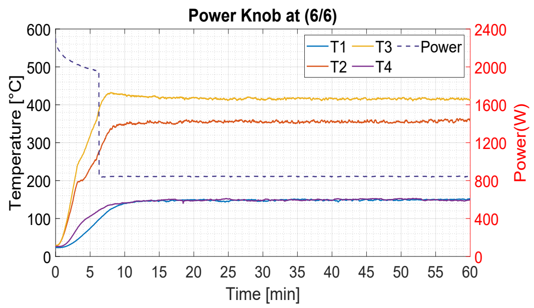
Figure 6.3: Temperature & power in cast iron pan with each cooktop

By turning knob to (9/9), power jumps to peak value of 2300 W and after 2 minutes goes down to 150 W and then repeats the cycle between 150 to 1200 W range for 15 minutes (see Figure 6.3 c). Afterwards, the pattern followed by power is similar between 150 to 500 W range.

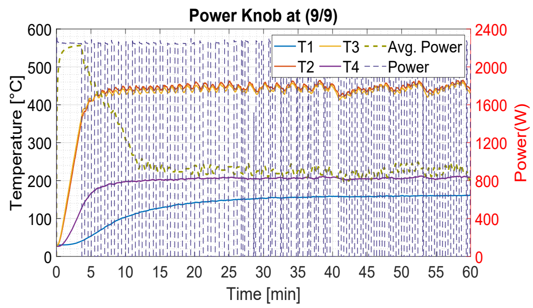
The temperature rise in cast iron pan with both electric and ceramic glass cooktop follows the similar pattern as it was without placing pan except temperature values are lower. On the induction cooktop, temperature rise is dependent on power behavior.

6.2.2 Carbon steel pan

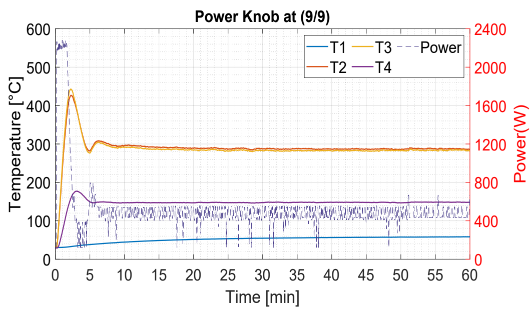
By placing carbon steel pan on both electric coil and ceramic glass cooktops (see Figure 6.4 a & b), power followed the similar pattern regardless of pan material. The temperature rise depicts similar trend with minor differences in both cooktops.



(a) Electric coil cooktop



(b) Ceramic glass cooktop



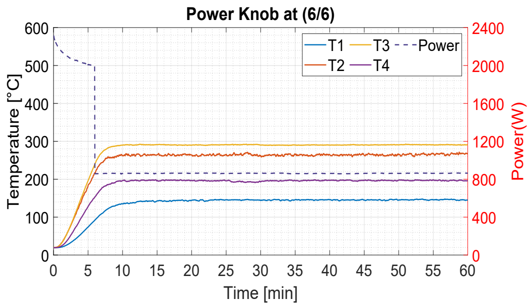
(c) Induction cooktop

Figure 6.4: Temperature & power in carbon steel pan with each cooktop

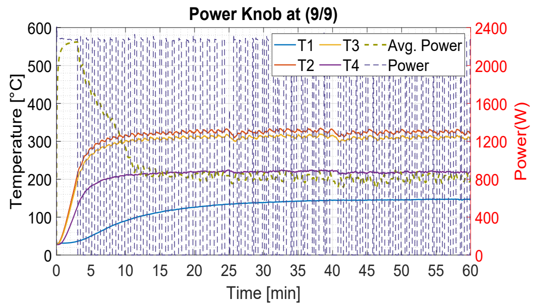
When induction cooktop is turned to full power (9/9) and carbon steel pan is placed over it, for the first 5 minutes, power pattern is like cast iron pan as shown in Figure 6.4 c. Afterwards, the power fluctuates between range of 150 W to 500 W. Following the power, temperature also reaches to it maximum value during first 2 minutes and then drops and remains steady state through the remaining operational time.

6.2.3 Aluminum pan-A

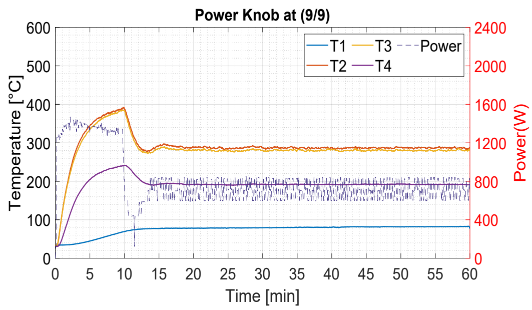
When Aluminum pan was placed on both electric coil and ceramic glass, the pattern followed by power was similar (see Figure 6.5 a & b). Also, the rise of temperature was similar except its values were lower compared to cast iron and carbon steel pans.



(a) Electric coil Cooktop



(b) Ceramic Glass Cooktop



(c) Induction Cooktop

Figure 6.5: Temperature & power in aluminum pan with each cooktop

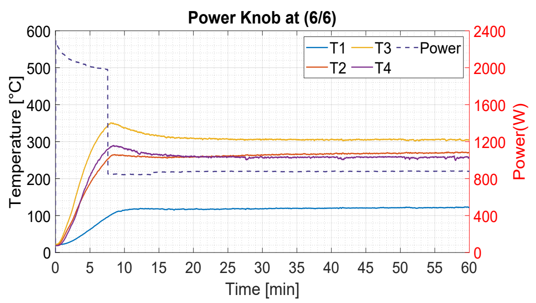
Compared to other pans, the power pattern of aluminum pan is different in induction cooktop as shown in Figure 6.5 c). The maximum power of 1400 W is attained for first 10 minutes and then it drops to 150 W and then the similar pattern of power is followed rest of time between range of 550 to 800 W. Also, temperature rises according to power behavior. As compared to other cooktops, higher temperature is achieved for first 10 minutes in aluminum pan with induction cooktop.

6.3 Additional tests

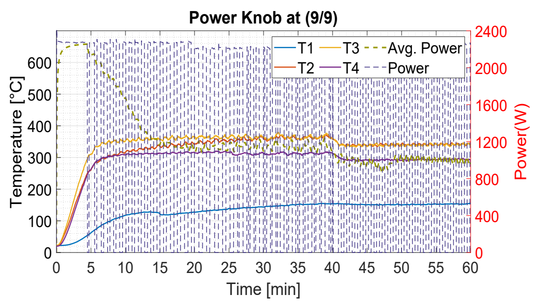
With aluminum pan B and oven tray, additional tests are performed with each cooktop.

6.3.1 Aluminum pan B

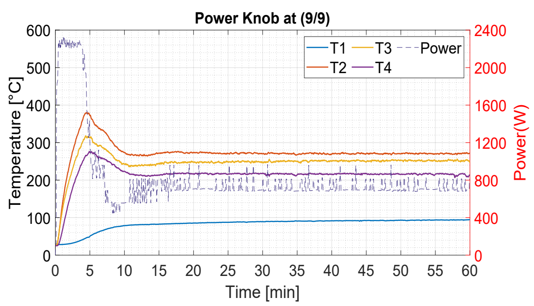
Figure 6.6 a & b shows that power with new aluminum pan followed the similar pattern in both electric coil and ceramic glass cooktop. In induction cooktop, power is significantly higher with new aluminum pan compared to previous. For initial 4 minutes it is 2300 W then it decreses for few minutes and afterwards remains between range of 600 W to 800 W (Figure 6.6c).



(a) Electric coil cooktop



(b) Ceramic glass cooktop



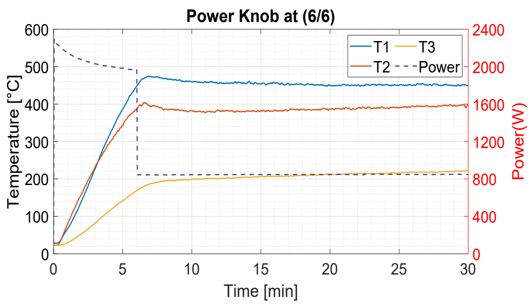
(c) Induction cooktop

Figure 6.6: Temperature & power in new aluminum pan with each cooktop

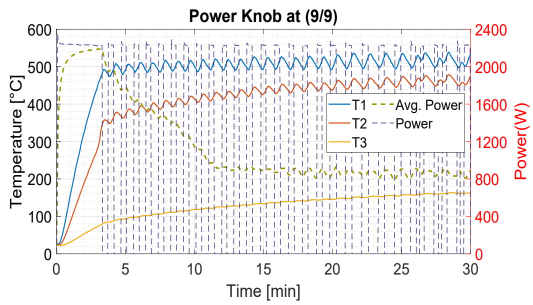
The temperature rise remained similar with induction cooktop. Also, in both electric coil and ceramic glass, temperature rise pattern remained similar except that values for temperature are increased with new pan. With induction cooktop, the power for both aluminum pans is different. It is due to the operation principle of induction cooktop because power transfer depends on the surface contact between heating surface and cookware. The surface contact area for aluminum pan-A is 200 mm whereas for aluminum pan-B is 210 mm. Temperature is similar with both cooktops but with aluminum pan-B, maximum temperature of 380 is achieved in 4 minutes whereas it takes 10 minutes in aluminum pan-B to achieve this temperature. Due to safety feature of induction cooktop, power is cut when this temperature is attained.

6.3.2 Oven tray

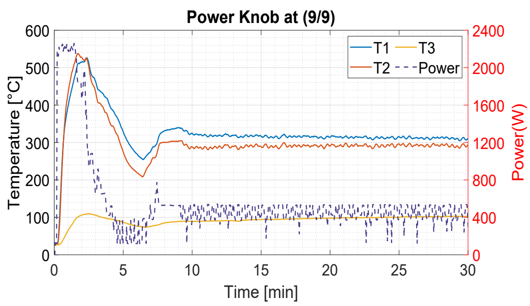
With oven tray, power followed similar pattern for each cooktop (Figure 6.7 a, b & c). The maximum temperature attained in electric coil and ceramic glass cooktop is 480°C and 510°C respectively. In induction cooktop, maximum temperature of oven tray is 530°C.



(a) Electric coil cooktop



(b) Ceramic glass cooktop



(c) Induction cooktop

Figure 6.7: Temperature & power in oven tray with each cooktop

Furthermore, the time required to reach the temperature in electric coil and ceramic glass cooktop is more than 5 minutes. Whereas in induction cooktop, oven tray can reach it maximum temperature in merely 2 minutes.

6.4 Maximum temperatures in cooktops and pans

Figure 6.8 shows that electric coil heating element attains maximum temperature of 330 °C and 620 °C with medium (3/6) and full (6/6) power, respectively. In ceramic glass, the maximum temperature with medium (5/9) and full (9/9) power is 380 °C and 590 °C, respectively. Cast iron and carbon steel pans reached to their maximum temperature of 510 °C and 465 °C in ceramic glass cooktop. However, aluminum pan attains it maximum temperature of 390 °C with induction cooktop followed by ceramic glass and electric coil cooktop.

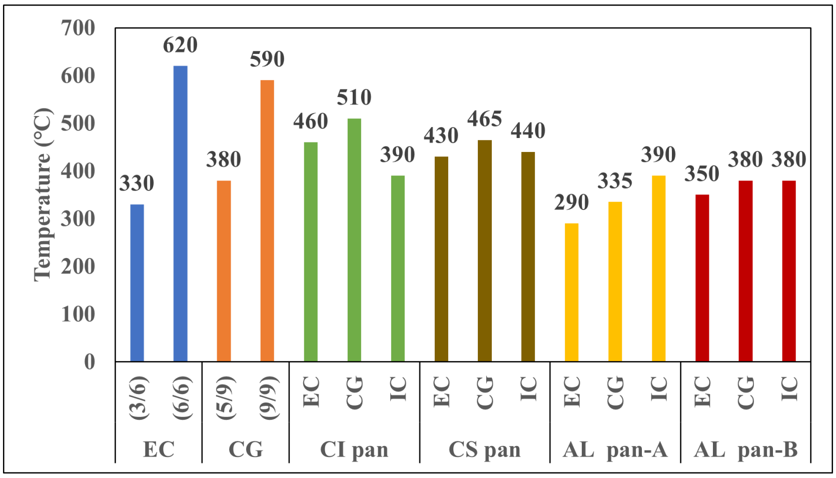


Figure 6.8: Maximum temperature achieved in cooktops and frying pans

Figure 6.9 shows the maximum temperatures as a function of measured electrical power in different cooktops and frying pans. The electrical power is measured at the time when temperature is at it maximum value. In all cooktops and pans, temperature is directly dependent on power. With maximum power, highest temperature is achieved.

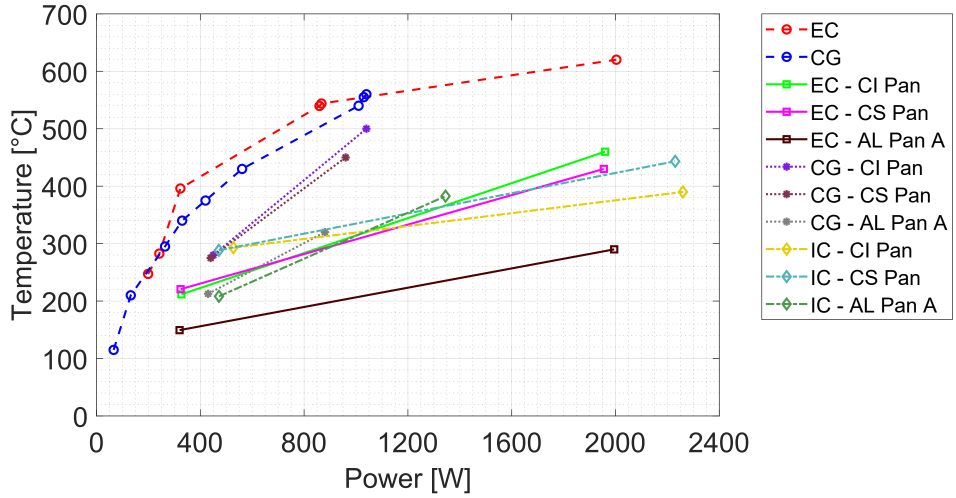


Figure 6.9: Maximum temperatures attained as function of electrical power in different cooktops and pans

6.5 Time to reach different temperatures in cooktops and pans

Figure 6.10 shows the time required by electric coil and ceramic glass cooktop to reach the different temperatures with maximum power setting. Ceramic glass cooktop can reach different temperature ranges fast as compared to electric coil cooktop.

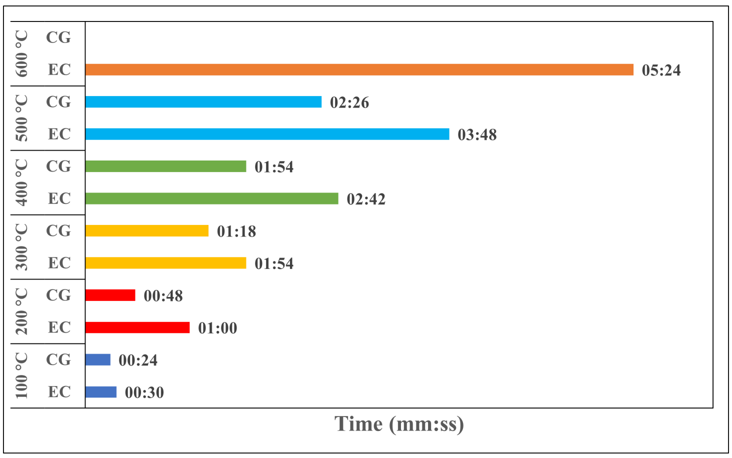


Figure 6.10: Time to reach different temperatures in EC & CG cooktop

Figure 6.11 compares the time required by each frying pan to reach different temperature ranges with electric coil cooktop. Among all, the carbon steel pan is fast compared to cast iron and aluminum pan.

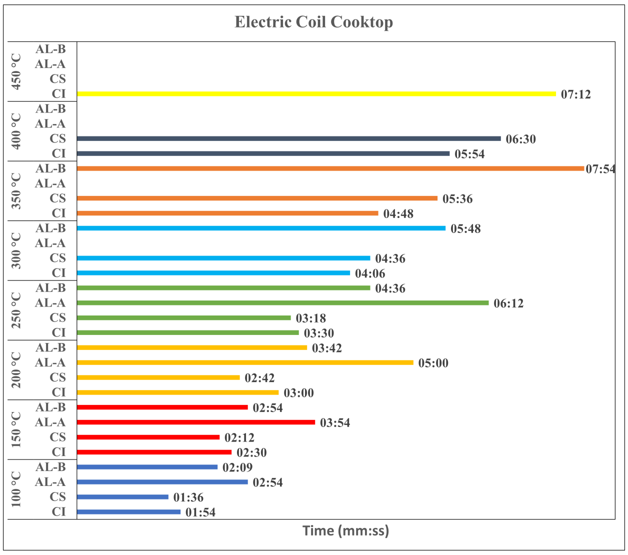


Figure 6.11: Time to reach different temperatures in EC cooktop with pans

When frying pans are placed on ceramic glass cooktop, then trend is different. Cast iron pan is slightly faster than carbon steel pan to reach different temperature ranges as shown in Figure 6.12.

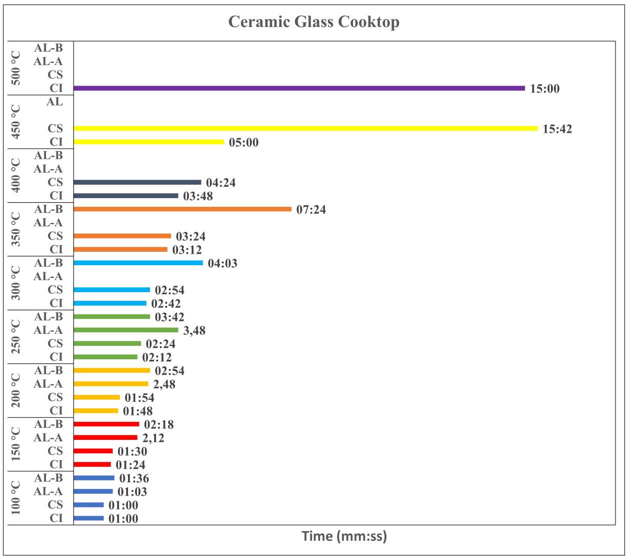


Figure 6.12: Time to reach different temperatures in CG cooktop with pans

Figure 6.13 shows that an induction cooktop follows the trend similar to electric coil cooktop. The carbon steel pan reacts faster compared to both cast iron and aluminum pand.

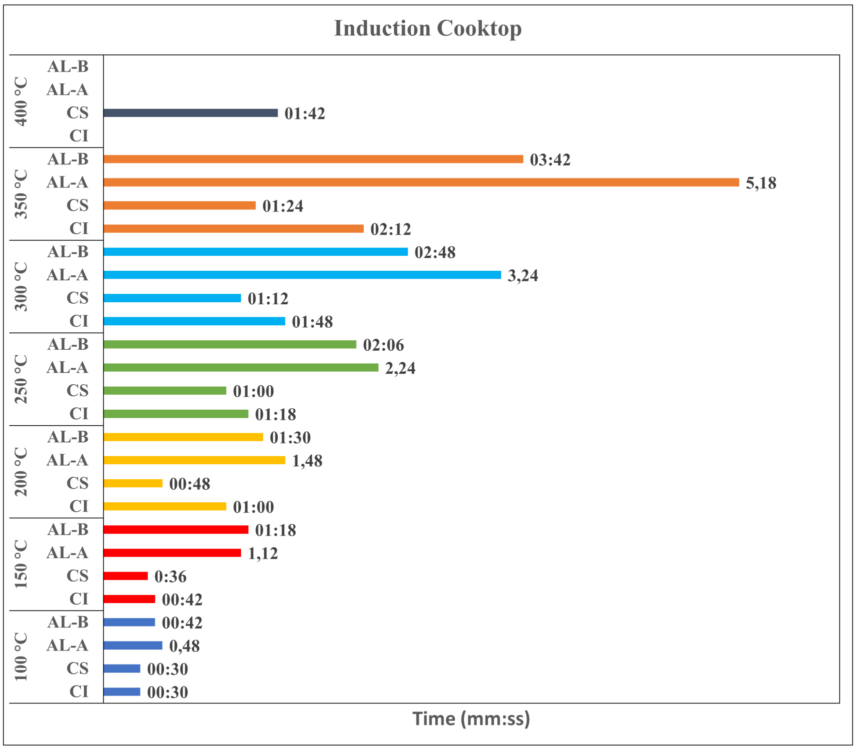
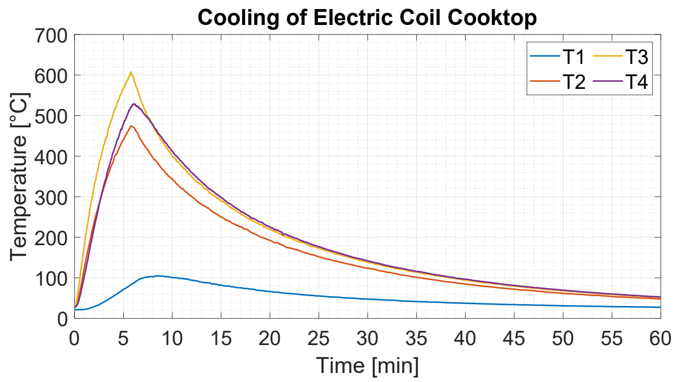


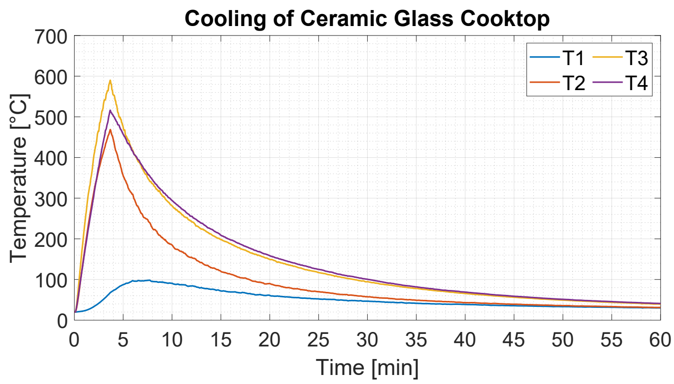
Figure 6.13: Time to reach different temperatures in IC cooktop with pans

6.6 Cooling time in electric coil and ceramic glass cooktop

In this section, time required for cooling of electric coil and ceramic glass cooktop is analyzed. The cooling behavior of the electric coil and ceramic glass cooktops was measured by turning the cooktops to maximum power and turning off the power when the peak temperature was reached. The results are shown in Figure 6.14. Due to its massive structure and higher heat capacity, the electric coil cooktop cools down at slower rate. After 30 minutes, the temperature of the ceramic glass has reached 100°C whereas in electric coil it is around 150°C.



(a) Electric coil cooktop



(b) Ceramic glass cooktop

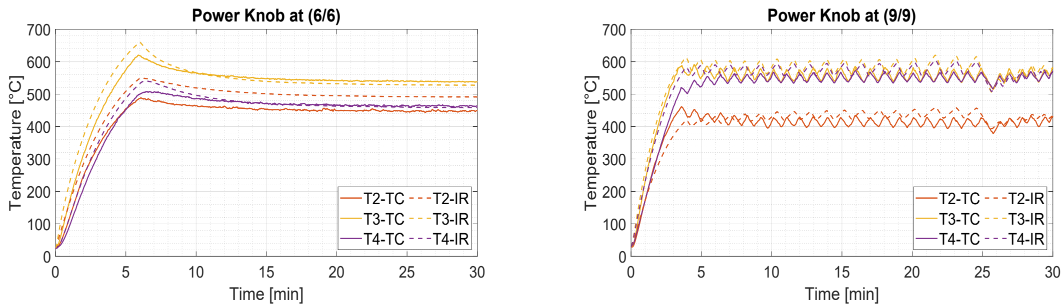
Figure 6.14: Cooling time of EC & CG cooktop

6.7 Temperature measurements by thermocouple and infrared camera

In this section, a comparison between temperature measured by thermocouples and infrared camera is made. For ceramic glass cooktop, IR camera emissivity was set to 0.85 but, for electric coil cooktop, it was 0.97. However, for all different types of pans, emissivity was set to 0.97. More results for TC and IR camera temperature comparisons can be found in appendix C.

6.7.1 Electric coil and ceramic glass cooktop

In the beginning of test, difference between thermocouple and infrared camera readings is larger in electric coil cooktop (see Figure 6.15a) but, this gap is decreased considerably with time. Compared to electric coil cooktop, temperature values are quite close to eachother in ceramic glass cooktop (see Figure 6.15b). More the time passes the more closer values are achieved.



(a) Electric coil cooktop

(b) Ceramic glass cooktop

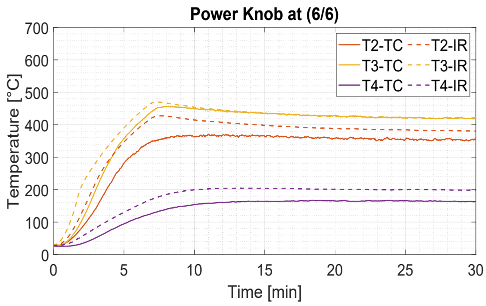
Figure 6.15: Comparing temperature by TC & IR camera in EC & CG cooktop

6.7.2 Cast iron pan with different cooktops

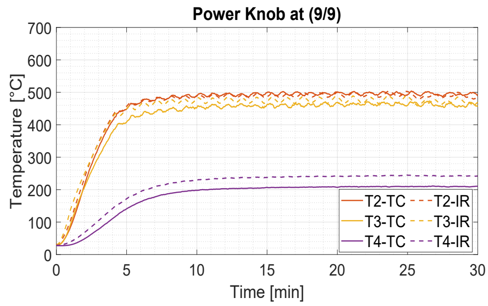
Figure 6.16 shows the results for temperature measured by thermocouple and infrared camera when cast iron pan was placed on each cooktop. In all cooktops, during first few minutes, the difference of temperature is large but with the lapse of operational time, it is decreased. Interestingly, the temperature values at position 4 (T4) exhibits large difference for all three cokktops when compared to that at position 2 (T2) and position 3 (T3). It is due to the fact that, at point 4 the curvature of pan is positioned which leads to large variation in temperature measured.

By placing the carbon steel pan on different cooktops, similar trends are realized. In the beginning of test, the difference between thermocuople and infrared readings is higher but gradually it is decreasing. The results are shown in appendix C3.

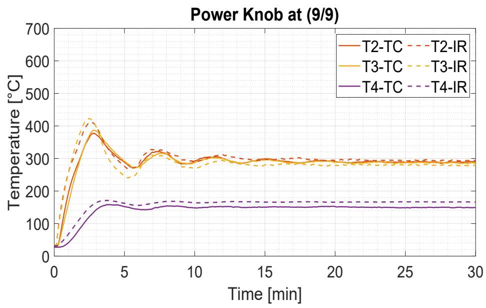
Among all analyzed pan materials, the difference in thermocuple and infrared camera readings is higher with aluminum pan A. From start to the end, a similar difference is observed in all three types of cooktops. Appendix C4 shows the results for aluminum pan A.



(a) Electric coil cooktop



(b) Ceramic glass cooktop



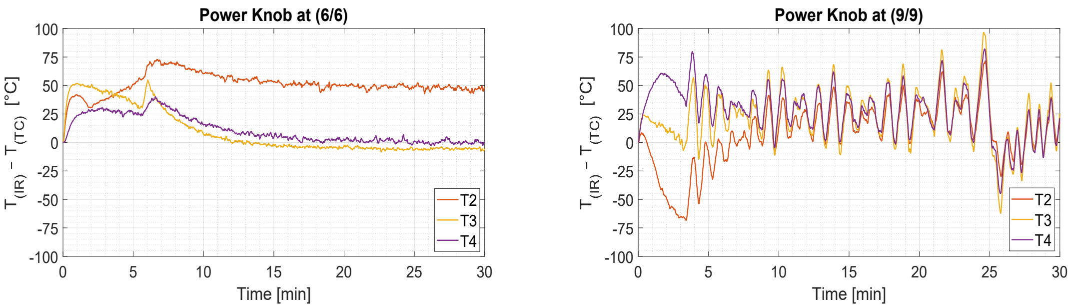
(c) Induction cooktop

Figure 6.16: Comparing temperature by TC and IR camera in cast iron pan

6.8 Temperature difference of TC & IR camera

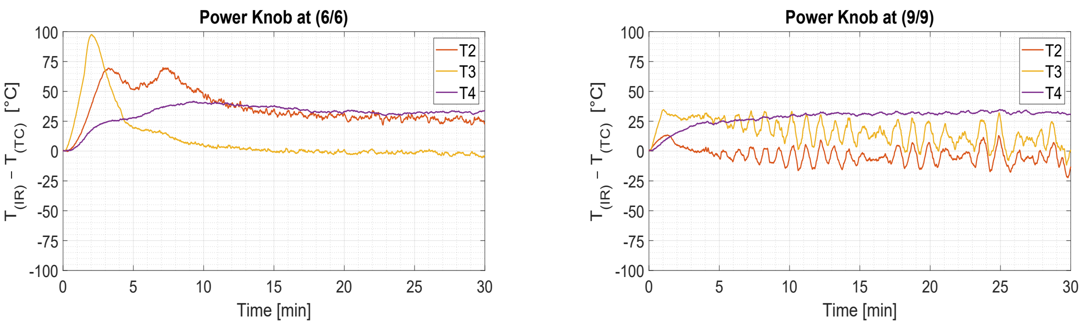
In this section, difference between measured values of infrared camera and thermocouple are shown. More results about the temperature differences between thermocouple and IR camera can be found in appendix D. In appendix E, images for cooktops and pans captured with IR camera are shown.

Figure 6.17 shows the temperature difference in infrared camera and thermcouple readings in electric coil and ceramic glass cooktop. Overall, temperature readings by thermal camera are higher than thermocouples in both cootkops. Initially these values are higher but with lapse of time, there can be seen a decrease. Ceramic glass cooktop shows relatively more fluctuation in temperature due to its power behavior.

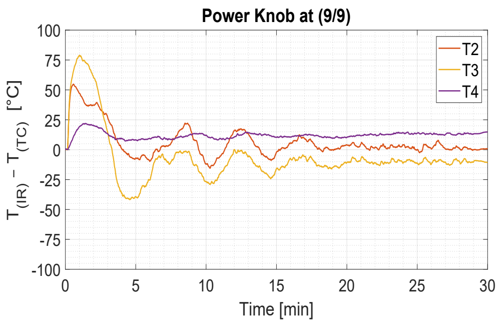


(a) Electic coil cooktop (b) Ceramic glass cooktop

Figure 6.17: Temperature difference of TC & IR camera in EC & CG cooktop



(a) Electric coil cooktop (b) Ceramic glass cooktop



(c) Induction cooktop

Figure 6.18: Temperature difference of TC & IR camera in cast iron pan

Figure 6.18 shows the results when cast iron pan is placed on all three cooktops. In electric coil and ceramic glass cooktop, similar pattern is obeserved i.e. temperature readings by infrared camera are higher than thermcouples most of the time. Due to power behavior of induction cooktop, more variability in temperatures can be seen. Overall, temperature difference lies between range of 25°C in all cooktops.

Carbon steel pan also showed the similar results as that of cast iron pan in all three cooktops except some minor differences (see appendix D3). Also, on average there is 25°C temperatures difference in all cooktops with carbon steel pan.

Compared to other pans, an aluminum pan-A showed slightly different pattern. With electric coil and ceramic glass, the difference have decreased however, in induction cooktop, temperature difference is increased. Results are shown in appendix D4.

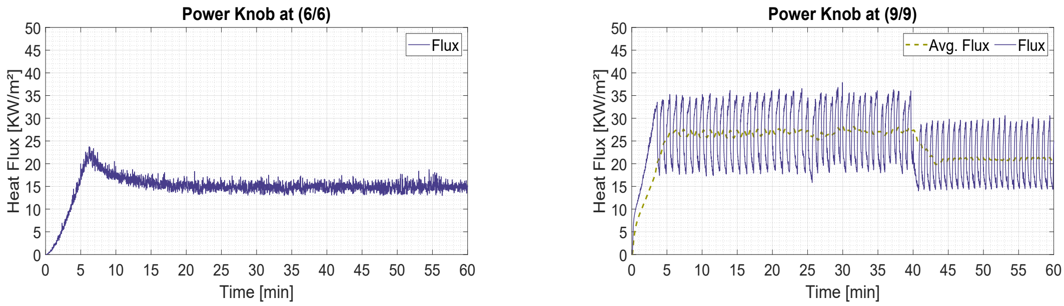
6.9 Heat Flux

In this section, the results of heat flux recorded in both electric coil and ceramic glass cooktop are shown. Also, comparison of heat flux is made with carbon steel pan on both cooktops.

6.9.1 Electric coil and ceramic glass cooktop

When electric coil cooktop is at maximum power (6/6) setting, heat flux increases significantly for first 6 minutes and reaches to maximum value of 24 KW/m^2 (Figure 6.19a). Afterwards it decreases gradually for next 10 minutes and then remains steady state with average value of 15 KW/m^2 for rest of operational time.

Figure 6.19b shows that by setting the power knob position maximum (9/9) in ceramic glass cooktop, within first few minutes heat flux reaches to value of 35 KW/m^2. Following the pattern of power in ceramic glass cooktop, it can be seen that heat flux fluctuates throughout the operational time. But the average heat flux is 28 KW/m^2 upto 40 minutes and then it is decreased to 20 KW/m^2.

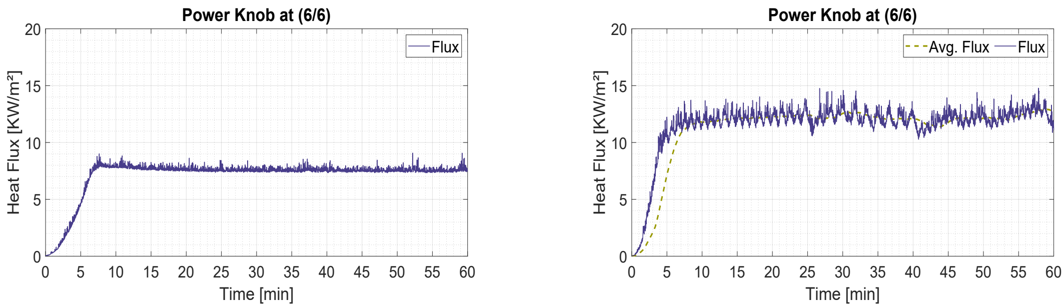


(a) Electic coil cooktop (b) Ceramic glass cooktop

Figure 6.19: Heat flux in EC & CG cooktops

6.9.2 Carbon steel pan

By placing carbon steel pan on electric coil and ceramic glass cooktop with maximum power setting, the heat flux increases abruptly for first few minutes then remain steady state in both cooktops (Figure 6.20). The average value of heat flux with carbon steel pan in electric coil and ceramic glass cooktop is 8 KW/m^2 and 12 KW/m^2 respectively.



(a) Electic coil cooktop (b) Ceramic glass cooktop

Figure 6.20: Heat flux in carbon steel pan with EC & CG cooktop

Chapter 7

Discussion

In this study, three different cooktops i.e electric coil, ceramic glass and induction were tested with different power settings. In addition, cast iron, carbon steel and aluminum pan were also tested with different power setting on each cooktop.

In electric coil and ceramic glass cooktops, the maximum surface temperature can reach upto 620°C and 590°C respectively within first few minutes at full power. The average steady state temperature for electric coil and ceramic glass cookotp is 465°C and 575°C respectively. The auto ignition temperature for many solid substances used in kitchen such as polypropylene, cardboard and paper towel are significantly lower than the temperature attained by these cooktops. So, there is a potential risk of ignition, if any of these materials is left unattended over the cooktops surface.

In electric coil cooktop at full power setting (6/6), cast iron and carbon steel pans can reach the maximum temperature of 460°C and 430°C respectively within 8 minutes. Different cooking oils such as canola, soyabean and corn oils have fire point temperature below the 400°C. Therefore, there are huge chances of ignition within these pans. With aluminum pan-A, maximum temperature of 290°C was attained in 10 minutes, which is well below the ignition temperature of different cooking oils. Additionally, an other aluminum pan of different brand (pan-B) was tested with similar procedure. The obtained result showed that maximum temperature of 350°C was achieved within 8 minutes. This temperature is very close to ignition temperature of different cooking oils, hence there is possibility of ignition with aluminum pan as well.

By turning ceramic glass cooktop on full power setting (9/9), cast iron and carbon steel pans can reach to the temperature of 510°C and 465°C respectively. Similar to electric coil cooktop, the temperature of pans with ceramic glass cooktop is high enough to easily ignite the different cooking oils. Aluminum pan-A and pan-B can reach to the temperatures of 335°C and 380°C respectively. Overall, these temperature values are close to ignition temperature of different cooking oils, hence potentially cause the ignition.

When induction cooktop is operated at full power setting, cast iron pan can reach to a temperature of 390°C in just 3 minutes and can easily ignite the different cooking oils. But, carbon steel pan can attain the maximum temperature of 440°C in merely 2 minutes which potentially lead to ignition of oils. Similarly, both aluminum pans, can achieve 390°C and can cause the ignition for different cooking oils.

Based on above discussion, all three cooktops with different pans can reach to the temperature that is sufficient to ignite the different type of cooking oils. In comparison to electric coil and ceramic glass cooktop, the induction cooktop can cause the ignition of oils rapidly.

In electric coil cooktop, power is set to maximum (6/6) and radiant heat flux is measured perpendicular to the heating surface. The distance gap between heat flux sensor and heating element is approximately 30 mm. The maximum heat flux of 22 KW/m^2 is reached in electric coil cooktop. Different solid substances such as wood, PMMA, polyethlene and polypropylene exhibit the critical heat flux in the range of 11 to 15 KW/m^2 with pilot ignition. Hence, there is a possility of ignition, if any of such material is placed very close to heating element in presence of pilot flame.

An average of 27 KW/m^2 radiant heat flux is measured in ceramic glass cooktop with similar method. Compared to electric coil cooktop, the radiant heat flux is higher in ceramic glass cooktop which suggests that there are more chances of ignition by different solids with pilot flame in ceramic glass cooktop.

Chapter 8

Conclusion

In current study, we performed a systematic thermal analysis of three different electric cooktops. Moreover, three different frying pans of different materials were thermally analyzed. These results can be used for evaluating the fire ignition potential in kitchens.

The results showed that the surface temperature of an electric coil cooktop can reach to 620°C in just 5 minutes. Similarly, ceramic glass cooktop can attained the surface temperature of 590°C in 4 minutes only. Comparatively, Ceramic glass cooktop heat up fast than electric coil cooktop. Both cooktops can ignite different substances such as cooking oils and solid materials. When power is turned off, both cooktops take longer time to cool down. Electric coil cooktop after 30 minutes of power cut off is still at 150°C and ceramic glass cooktop is at around 100°C .

Furthermore, trend of temperature rise remained similar with different pan materials. In all three cooktops, within first few minutes, cast iron, carbon steel, and aluminum pans can easily reach to the temperature at which different cooking oils and solid substances can be ignited. Compared to aluminum pan, carbon steel and cast iron pans can reach to the maximum temperature in short interval with all three cooktops. Among all three cooktops, electric coil cooktop heats up pans at lower rate than ceramic glass and induction cooktop. But, compared to electric coil and ceramic glass cooktops, induction cooktop can heat up different frying pans rapidly. Overall, in all three cooktops, unattended cooking with these pans can lead to a risk of getting ignition.

Our results provide the information to compare the different types of electric cooktops and pan materials from ignition perspective.

Bibliography

[1] Marty Ahrens. Home cooking fires. *National Fire Protection Association, Quincy, MA*, 2019.

[2] Jukka Lepisto, Laura Kuurne and Tarja Ojala. Liesipalojen kokonaiskuva ja liesiturvallisuutta vaarantavat tekijat. *Fire Research Seminar, The Finnish National Rescue Association SPEK*, 2021.

[3] London Fire Brigade. London flat fire. https://www.london-fire.gov.uk/incidents/2021/january/flat-fire-beckenham/, 2021.

[4] NFPA. Pennsylvania flat fire. https://www.nfpa.org/News-and-Research/Publications-and-Media/NFPA-Journal/2018/January-February-2018/News-and-Analysis/Firewatch, 2018.

[5] Mrs. Ashford. Innovation and evolution. https://www.coursehero.com/file/p3tvhpc/The-modern-kitchen-range-was-invented-by-Sir-Benjamin-Thompson-Count-Rumford-in.

[6] History of cooktops. https://www.appliancesconnection.com/blog/cooktop-history, 2018.

[7] R Cowen. *Relish: the extraordinary life of Alexis Soyer, Victorian celebrity chef*. Hachette UK, 2010.

[8] GEO. B. SIMPSON. improved electrical heating apparatus. https://patents.google.com/patent/US25532A/en, 1859.

[9] How electric stove work. https://www.hunker.com/13409456/how-does-an-electric-stove-work.

[10] Andersson, Lina and Marie Lindström. Design of top of the range ceramic cooktop with emphasis on usability and interface, 2006.

[11] Necip Suat Canarslan and Özgür Sevgi Canarslan. Combustion synthesis of sic-mosi2-al2o3 composites. *Ceramics International*, 45(12):14505–14509, 2019.

[12] Transfer of energy in electrical appliances. https://homeguides.sfgate.com/transfer-energy-electrical-appliances-62247.html.

[13] Ashish. How does an induction cooktop work? https://www.scienceabc.com/innovation/how-does-an-induction-cooktop-work.html, 2019.

[14] Micah Sweeney, Jeff Dols, Brian Fortenbery, and Frank Sharp. Induction cooking technology design and assessment. *ACEEE Summer Study on Energy Efficiency in Buildings. Berkeley, CA: Berkeley National Laboratory*, 2014.

[15] Solid disk electric cooktop. https://www.homedepot.com/p/Summit-Appliance-24-in-Solid-Disk-Electric-Cooktop-in-Stainless-Steel-with-4-Elements-CSD4B24/308904755.

[16] Types of stoves. https://athomemum.com/new-design-electric-stove.html.

[17] 21 different types of stoves/cooktops. https://www.homestratosphere.com/types-of-stoves-cooktops/.

[18] Bertazzoni professional series cooktop. https://www.ajmadison.com/cgi-bin/ajmadison/P244CERNE.html.

[19] 90cm 4 zone induction cooktop with boilprotect. https://www.westinghouse.co.nz/cooking/cooktops/whi945bc/.

[20] Italian manufacturer bertazzoni unveils ingenious modular cooktop. https://homeiq.wordpress.com/2012/05/25/italian-manufacturer-bertazzoni-unveils-ingenious-modular-cooktop/.

[21] Ge pp9830djbb profile series electric cooktop with 4 burners and 3-speed downdraft exhaust system. https://www.amazon.com/GE-PP9830DJBB-Smoothtop-Electric-Downdraft/dp/B00W8T3Y8G.

[22] Merel Ruiter & Jana Domrose. Fatal residential fires in europe. 2018.

[23] Grand View Research. Household cooking appliance market size, share trends report household cooking appliance market size, share trends analysis report by product (cooktops cooking ranges, ovens, specialized appliances), by region, and segment forecasts, 2019 - 2025. `https://www.grandviewresearch.com/industry-analysis/household-cooking-appliances-market`, 2019.

[24] FEMA. Structure cooking fires. `https://nfa.usfa.fema.gov/downloads/pdf/statistics/v5i6.pdf`, 2005.

[25] Md Iftekharul Mobin, Md Abid-Ar-Rafi, Md Neamul Islam, and Md Rifat Hasan. An intelligent fire detection and mitigation system safe from fire (sff). *International Journal of Computer Applications*, 133(6):1–7, 2016.

[26] Seppo Lautamies. Stove guards prevent accidents. `https://www.sgs.com/en/news/2017/01/stove-guards-prevent-accidents`, 2017.

[27] What is bs en 50615? `http://www.unicook.co.uk/blog/what-is-bs-en-50615/`, 2018.

[28] New standard for prevention of cooktop fires. `https://nemko.com/news/new-standard-prevention-cooktop-fires`, 2015.

[29] D Drysdale. Ignition: the initiation of flaming combustion. *An introduction to fire dynamics*, pages 225–275, 2011.

[30] José Torero. Flaming ignition of solid fuels. In *SFPE handbook of fire protection engineering*, pages 633–661. Springer, 2016.

[31] Xinshuai Liu and Zhenyi Liu. Research progress on flash point prediction. *Journal of Chemical & Engineering Data*, 55(9):2943–2950, 2010.

[32] M Vidal, WJ Rogers, and MS Mannan. Prediction of minimum flash point behaviour for binary mixtures. *Process Safety and Environmental Protection*, 84(1):1–9, 2006.

[33] Dong-Myeong Ha. The measurement of combustible characteristics of n-undecane. *Fire Science and Engineering*, 27(2):11–17, 2013.

[34] Dinaburg, Joshua B. and Daniel T. Gottuk. Development of standardized cooking fires for evaluation of prevention technologies: phase one data analysis. *Quincy, MA: National Fire Protection Association*, 2013.

[35] Harinageswara Rao Katragadda, Andrés Fullana, Sukh Sidhu, and Ángel A Carbonell-Barrachina. Emissions of volatile aldehydes from heated cooking oils. *Food Chemistry*, 120(1):59–65, 2010.

[36] Ayhan Demirbas and Gönenç Arin. An overview of biomass pyrolysis. *Energy sources*, 24(5):471–482, 2002.

[37] Shadi Moqbel, Debra Reinhart, and Ruey-Hung Chen. Factors influencing spontaneous combustion of solid waste. *Waste Management*, 30(8-9):1600–1607, 2010.

[38] Ignition temperature of polypropylene. `https://www.acplasticsinc.com/techsheets/Polypropylene_MSDS.pdf`.

[39] Ignition temperature of card board. `https://www.tis-gdv.de/tis_e/ware/papier/wellpapp/wellpapp-htm/`.

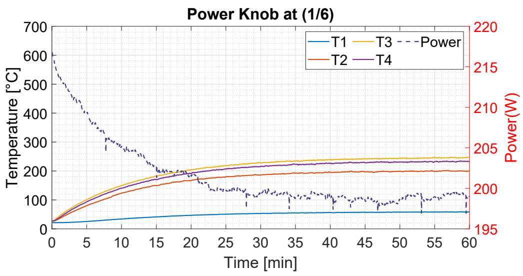
[40] Ignition temperature of paper towel. `https://kitchengen.com/can-you-put-paper-towels-in-the-oven/`.

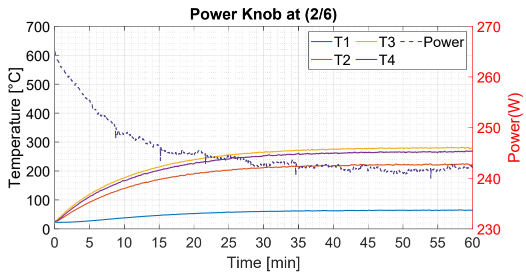
[41] David Rich, Chris Lautenberger, Jose L Torero, James G Quintiere, and Carlos Fernandez-Pello. Mass flux of combustible solids at piloted ignition. *Proceedings of the Combustion Institute*, 31(2):2653–2660, 2007.

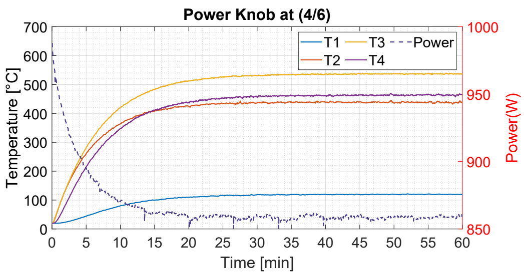
Appendix A

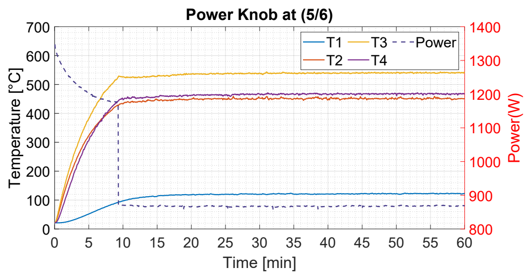
Temperature & power in cook-tops

A.1 Electric coil cooktop

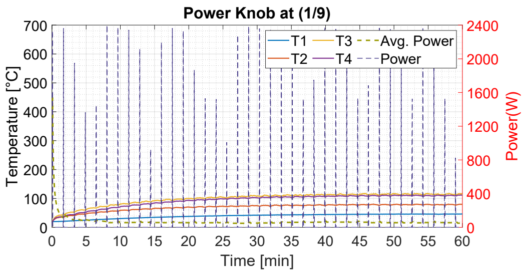


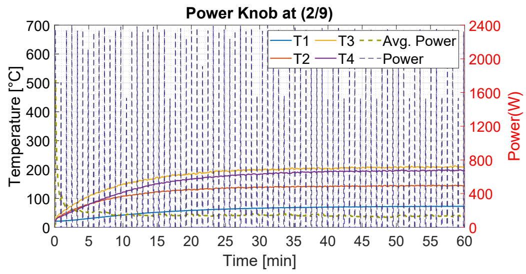


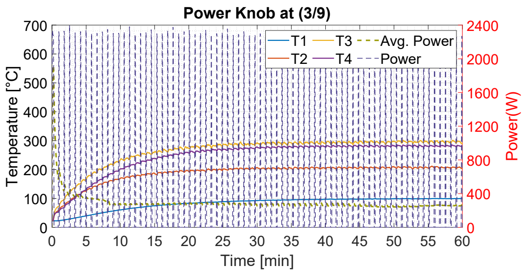


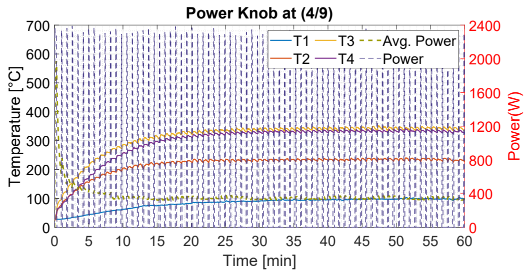


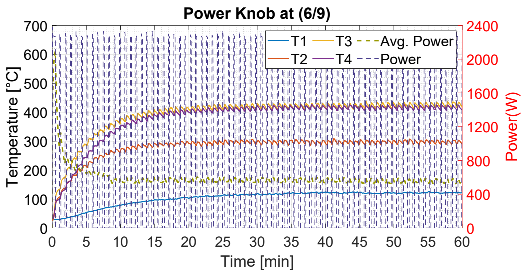
A.2 Ceramic glass cooktop

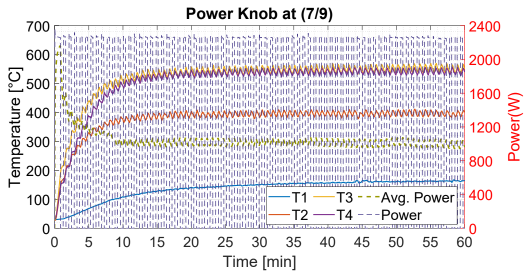


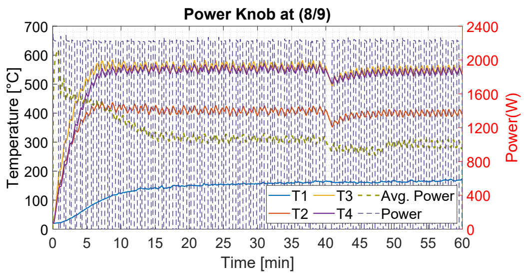








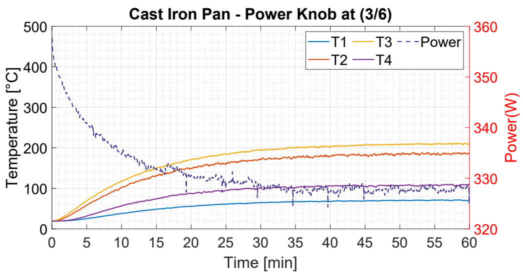


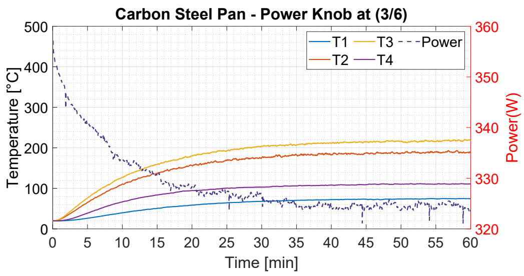


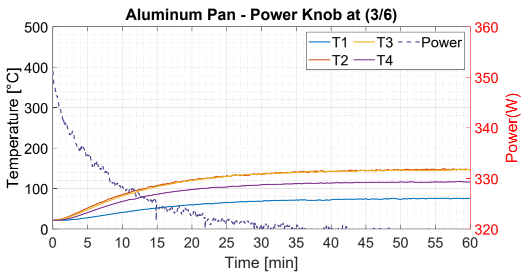
Appendix B

Temperature & power in different pans

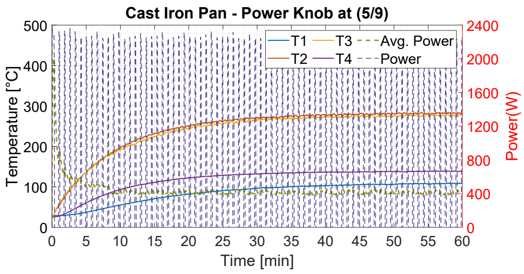
B.1 Electric coil cooktop

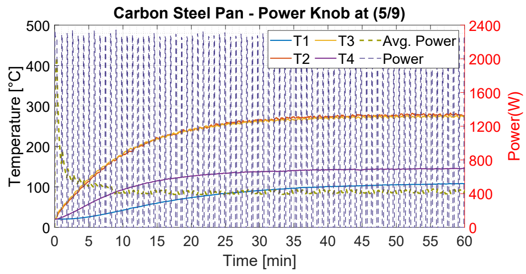


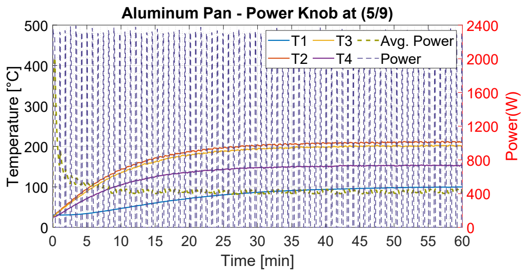




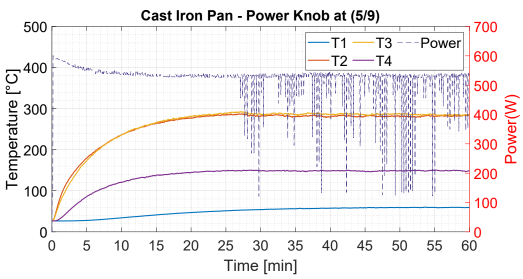
B.2 Ceramic glass cooktop

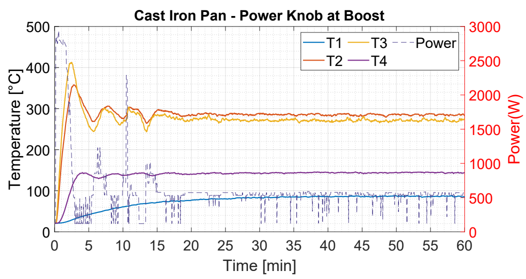


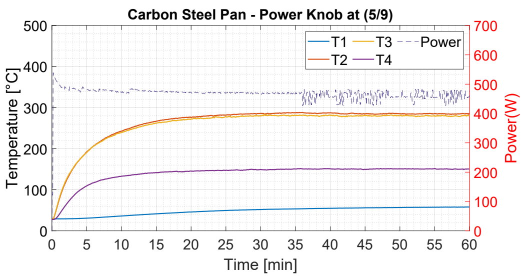


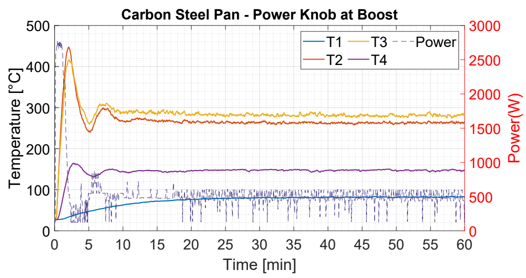


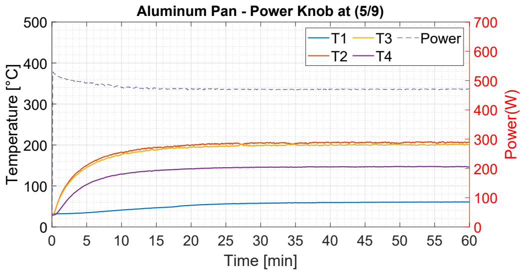
B.3 Induction cooktop

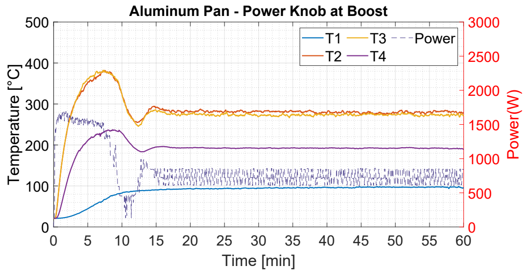








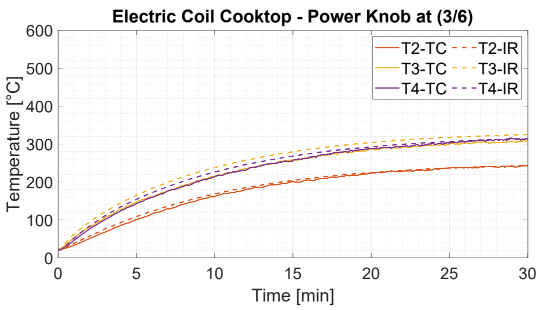

Aluminum Pan - Power Knob at (5/9)
T1
T2
T3
T4
Power
Temperature [°C]
Power(W)
Time [min]
0
100
200
300
400
500
600
700
0
5
10
15
20
25
30
35
40
45
50
55
60

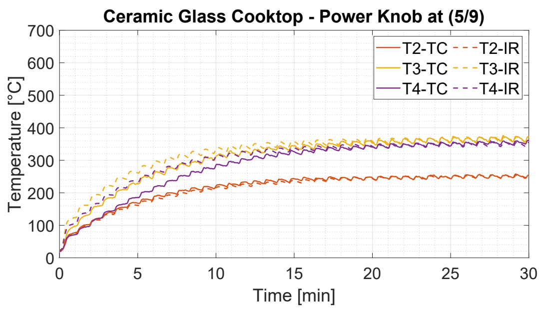

Aluminum Pan - Power Knob at Boost
T1
T2
T3
T4
Power
Temperature [°C]
Power(W)
Time [min]
0
100
200
300
400
500
1000
1500
2000
2500
3000
0
5
10
15
20
25
30
35
40
45
50
55
60

Appendix C

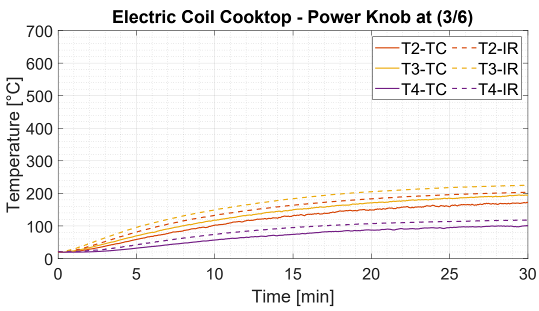
Temperature by TC & IR camera

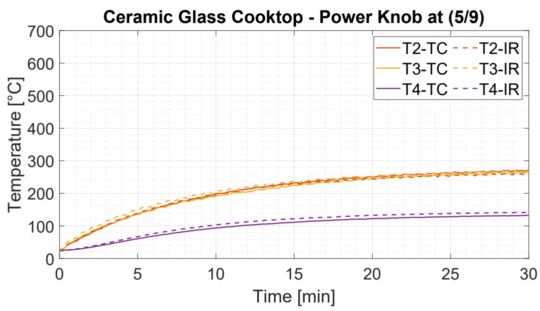
C.1 Electric coil and ceramic glass cooktop

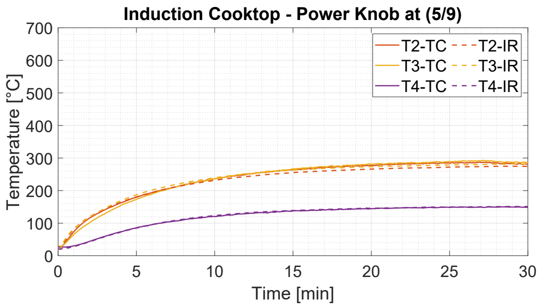




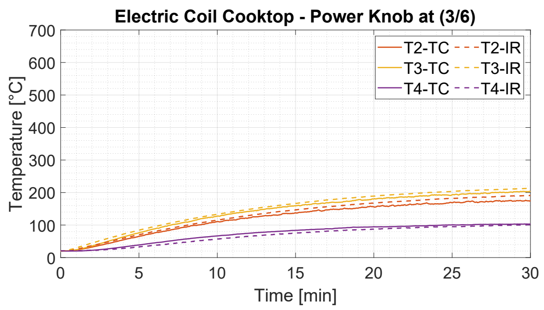
C.2 Cast iron pan

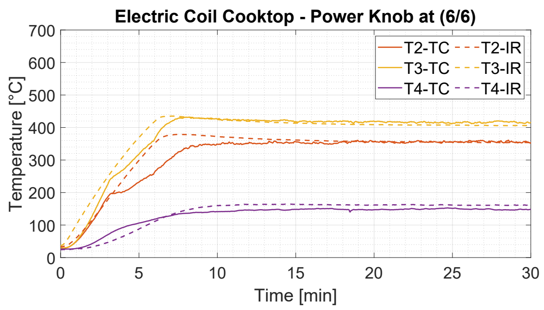


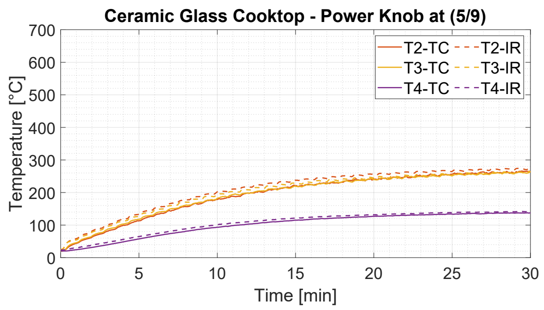


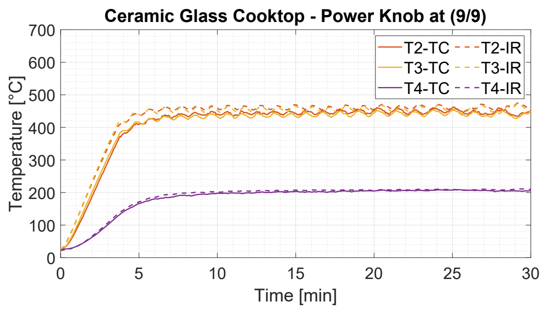


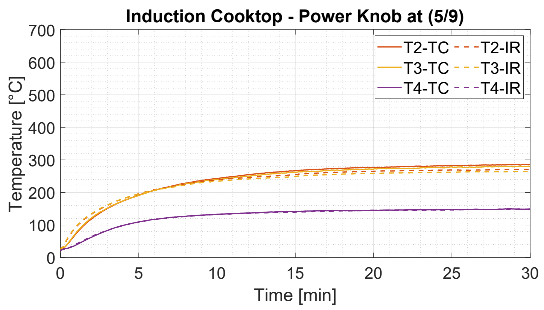
C.3 Carbon steel pan

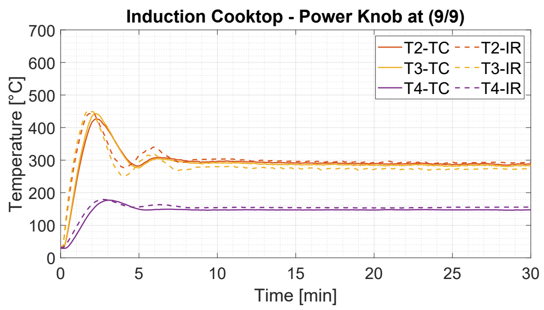




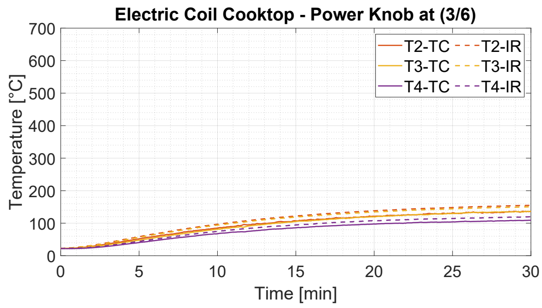


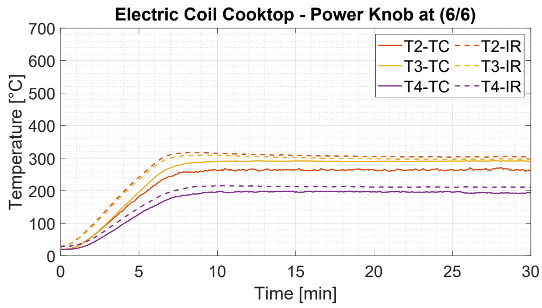


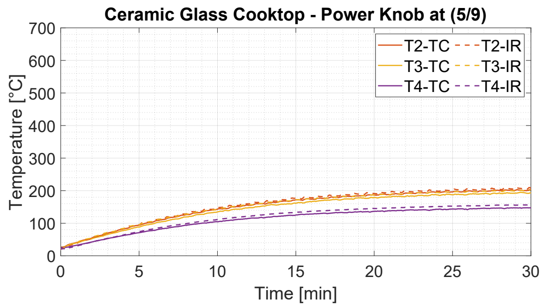


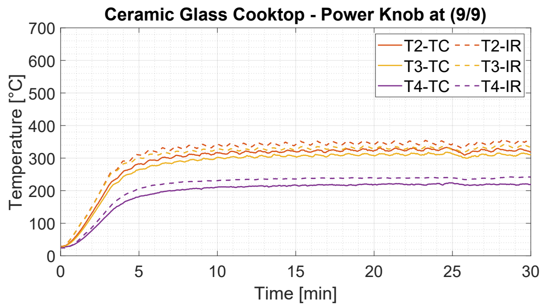


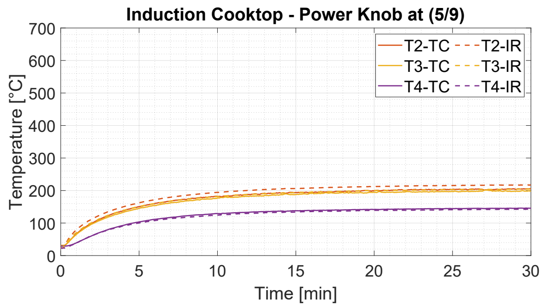
C.4 Aluminum pan-A

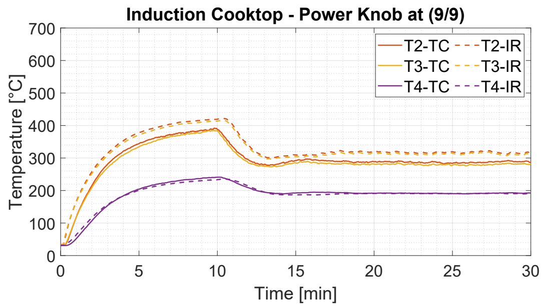








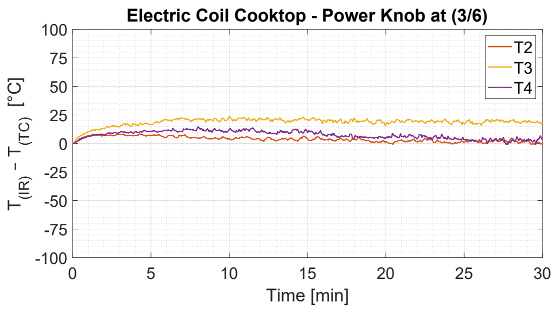


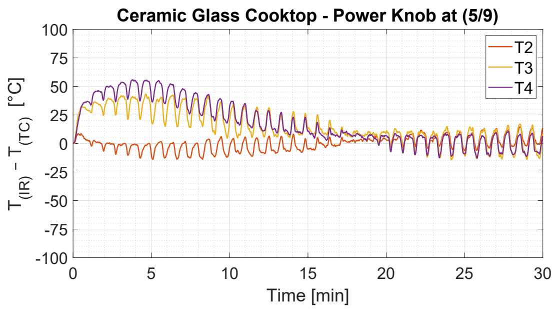


Appendix D

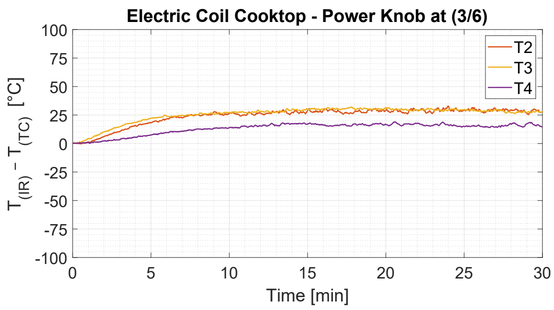
Temperature difference of TC & IR camera

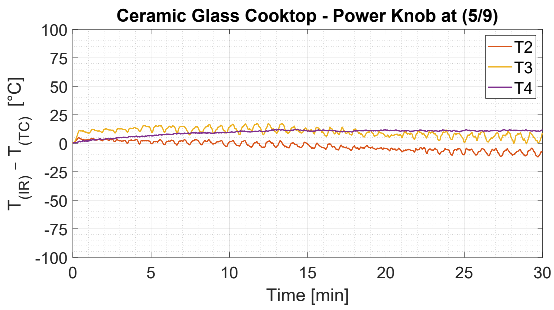
D.1 Electric coil and ceramic glass cooktop

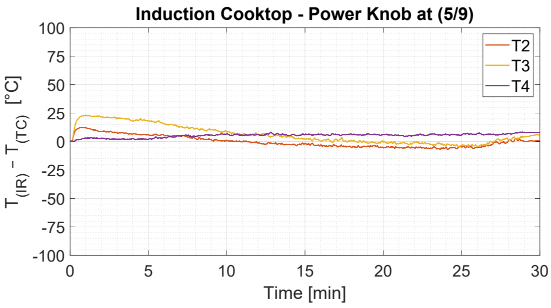




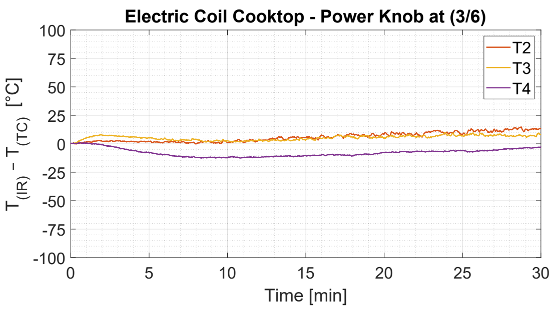
D.2 Cast iron pan

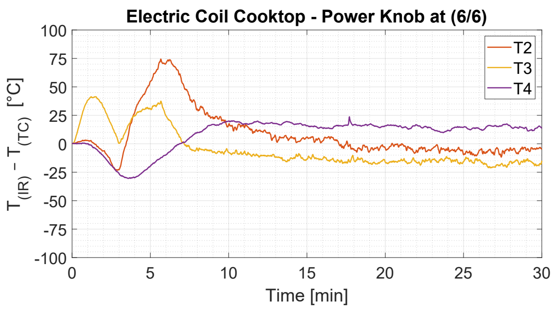


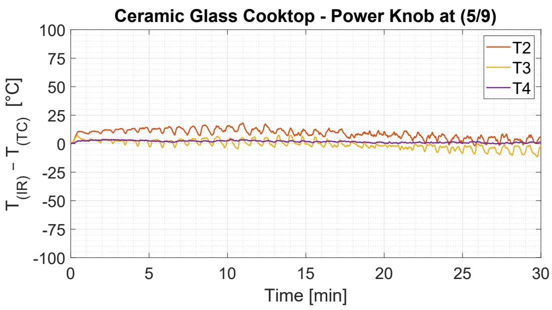


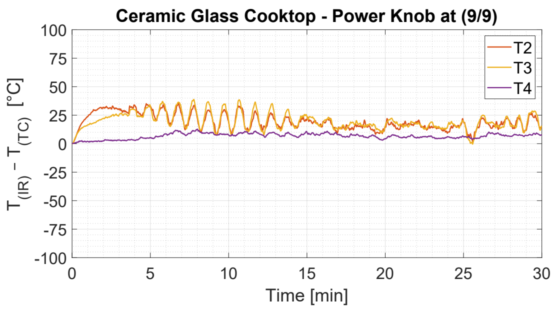


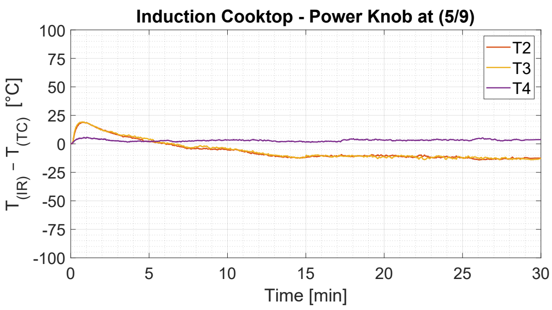
D.3 Carbon steel pan

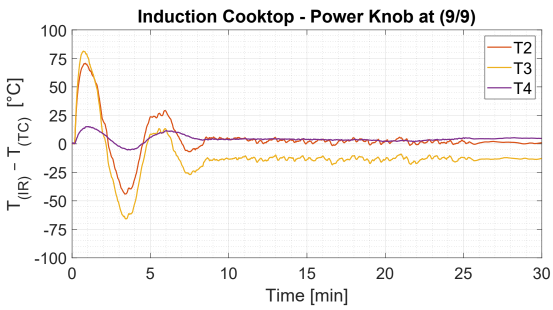




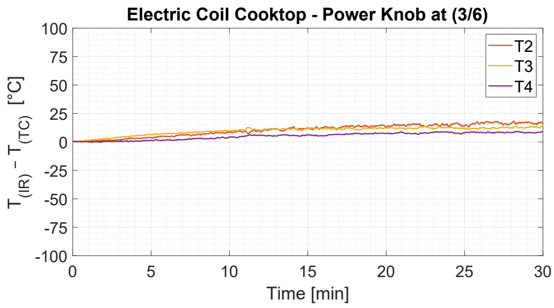


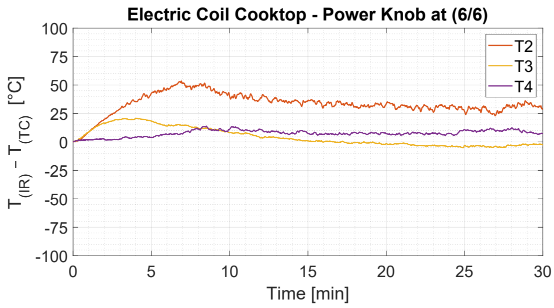


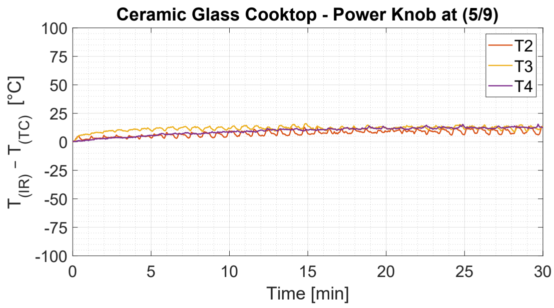


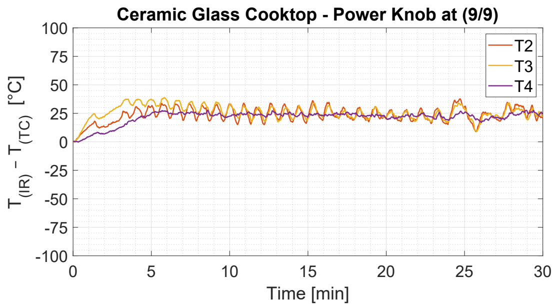


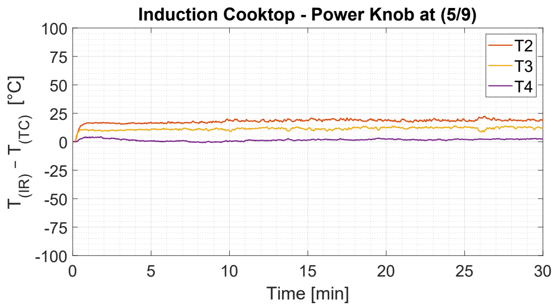
D.4 Aluminum pan-A

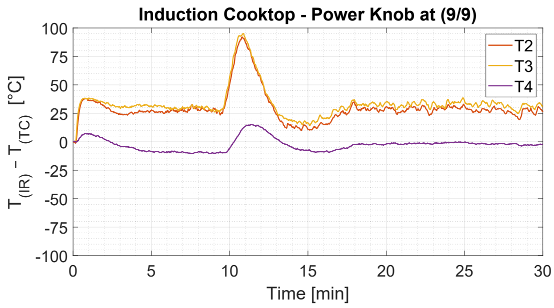








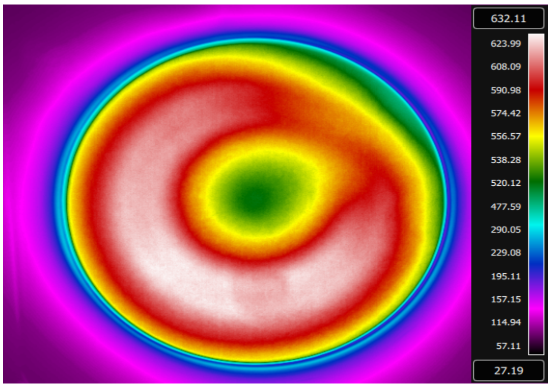




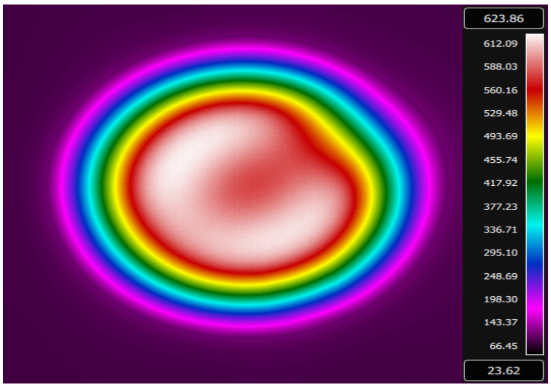
Appendix E

Images of cooktops and pans with IR camera

E.1 Electric coil and ceramic class cooktop

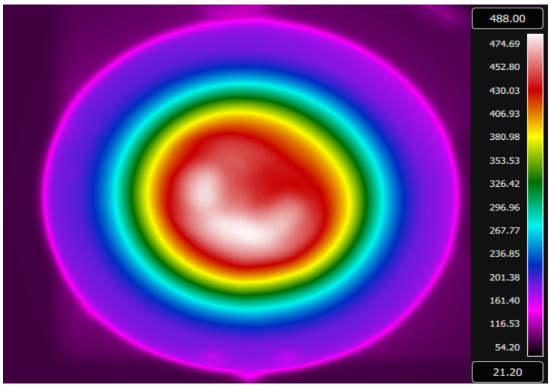


(a) Electric coil Cooktop

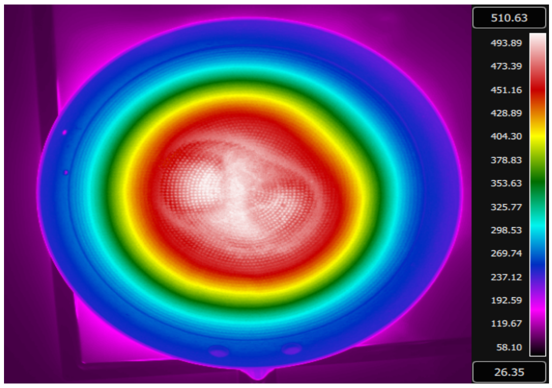


(b) Ceramic Glass Cooktop

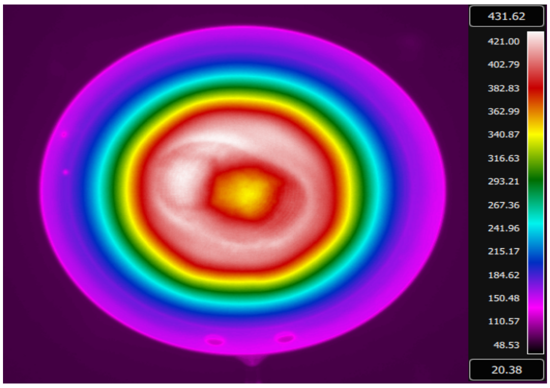
E.2 Cast iron pan



(c) Electric coil Cooktop

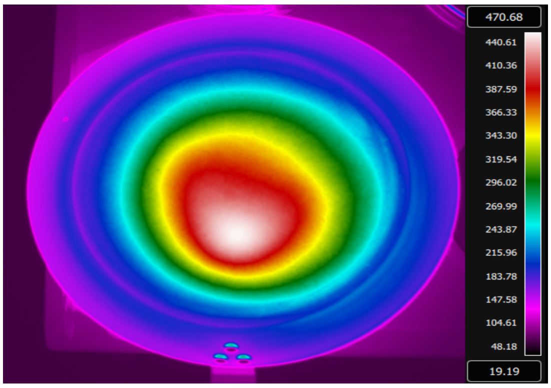


(d) Ceramic Glass Cooktop

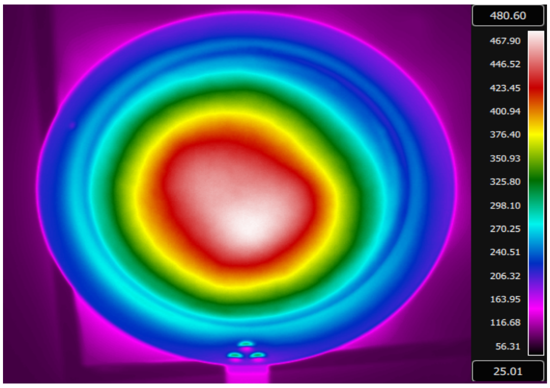


(e) Induction Cooktop

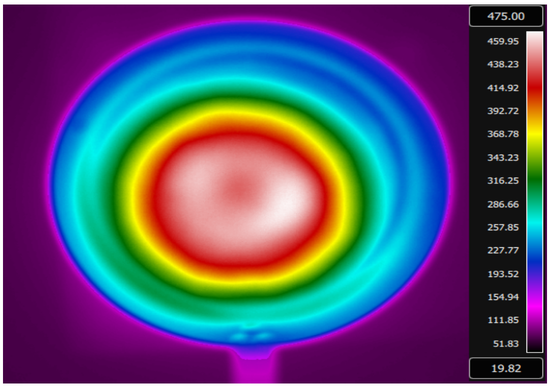
E.3 Carbon steel pan



(f) Electric coil Cooktop

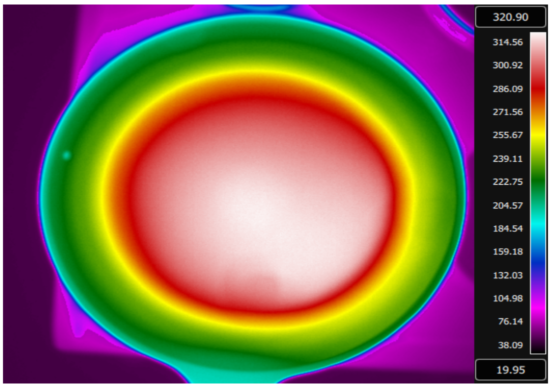


(g) Ceramic Glass Cooktop

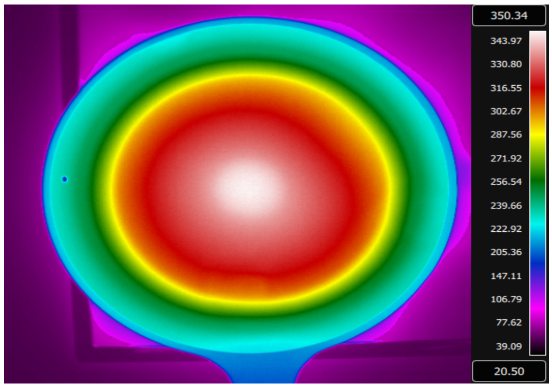


(h) Induction Cooktop

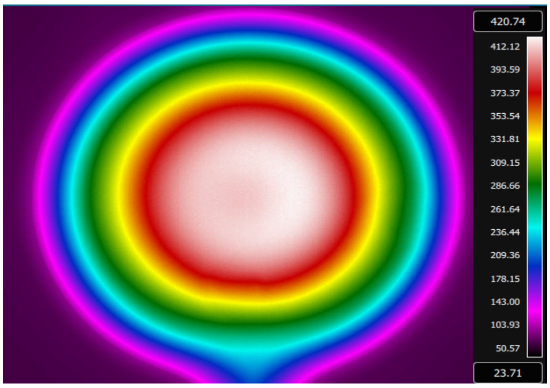
E.4 Aluminum pan-A



(i) Electric coil Cooktop



(j) Ceramic Glass Cooktop



(k) Induction Cooktop