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Exploring the thermal characteristics, ignitions and heat release of oils and solid items at electric cooktops

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A R T I C L E I N F O

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A B S T R A C T

Kitchen is the most common origin of residential fires, and usually the fire starts from a cooktop. To increase the understanding of such fires, we measured the electric power and surface temperatures of three different cooktops and four frying pans, and measured the ignition times and heat release rates (HRR) from cooking oils, butter and four different solid items (pizza box, pot holder, paper towel roll, LDPE bags). The estimated ignition probability of oils and butter was 0.44 ± 0.13, with an ignition time of 309 ± 81 s and peak HRR of 300–600 kW/m^2. Solid items ignited with 0.80 ± 0.10 likelihood in 378 ± 228 s, reaching higher temperatures at ignition compared to oils. LDPE bags posed the highest risk due to their propensity to ignite, melt, and burn with peak HRR exceeding 2000 kW/m^2. The ignition times were mainly controlled by the cooktop heating, while the material processes delayed the ignitions by 23%. Stove guards (EN 50615 cat. B) activated before ignition in all tests, except for the pizza box and pot holder. Ignition prevention was not tested, though. Further development of the stove guard standard is therefore necessary to effectively prevent fires originating from auxiliary materials.

1. Introduction

Kitchen is the most common room of origin for dwelling fires in many countries [1], and cooktop fire safety is an essential target of improvement when aiming at reducing the residential fires and associated losses. According to a NFPA report, cooking was the leading cause of home fires and injuries, and the second cause for fire deaths in North America during 2014–2018 [2]. Cooktops were identified as the cause of about 61% of the kitchen fires, accounting for 87% of deaths, and 78% of injuries by cooking fires. According to the Finnish statistics, about one third of residential fires [3] and 8% of fatal fires [4] originate from cooking. The leading causes for cooktop fires in Finland are additional materials stored on the stove and unsupervised cooking, resulting from forgetting, influence of alcohol or drugs, other factors causing reduced awareness, or a mistake, such as turning on a wrong heating element [5]. Other causes include misuse of materials, failure to clean and unintentional turning on or not turning off.

Previous studies of the cooktop fires have primarily examined the influence of cooktop [6,7] and fuel [7–10] types, as well as the quantity of cooking oil [6,11]. These studies have focused on aspects such as ignition time [6,10,11], heat release rate (HRR) [6,8,11,12], consequence modelling [13], and detection and suppression [7,9,14,15]. By considering the effects of oil type and quantity in conjunction with variations in cooking oil consumption [16], it becomes evident that regional and cultural differences in cooking practices are likely to play a role in cooking-related ignitions and fires. Interestingly, the vast majority of research conducted across various studies has adopted cooking oil as a fuel source, while neglecting to explore the impact of other materials that can ignite and contribute to fires.

Electric cooktops can be classified in three main categories: electric coil, ceramic glass (smooth top), and induction cooktops. While gas cooktops still have the highest share (38%) of the North America cooktop market, electric cooktops (other than induction) (34%) and induction cooktops (22%) increase in popularity [17]. In Finland, practically all cooktops are powered by electricity, and about 30% of the new cooktops were based on induction technology in 2016 [18]. According to NFPA, the households with electric cooktops have higher likelihood of catching cooking fire than those using other types of cooktops [2]. In the electric coil and ceramic glass cooktops, the heating of the cookware is based on heat conduction, which means that a hot surface is available as an ignition source when the cooktop is on. Induction cooktops, on the other hand, heat up ferromagnetic cookware

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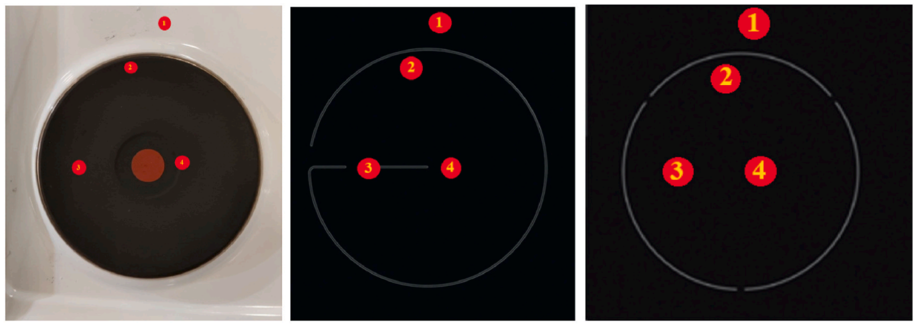


(a) Electric coil cooktop (b) Ceramic glass cooktop (c) Induction cooktop

Fig. 1. Placement of surface thermocouples on cooktops.

Table 1
Specifications of the cooktops and the specific heating elements used.

Cooktop type	Acronym	Brand and model	Heating element	
			Diameter (mm)	Power (W)
Electric coil	EC	Rosenlew RKL5100	180	2000
Ceramic glass	CG	Rosenlew RHRN642X	210	2200
Induction	IC	HOI620S/622S	210	2300–2800

(typically iron or steel) directly, and hot surfaces are limited to those of the cookware [19].

In addition to cooktop safety features, such as timers, additional fire protection solutions have been developed for kitchens. Stove guards are devices that monitor the conditions on the cooktop using smoke, heat, or movement sensors, or their combinations [20]. After detection they either turn off the electricity or attempt to suppress an already ignited fire, or both, besides giving an alarm signal. Stove guards are tested and classified according to EN 50615 standard, which in its current form is solely based on cooking oil fires [21]. The commercial stove guards can be expected to detect or prevent oil fires with high reliability, but the performance against the ignition of other materials is not known.

The goal of this research is to increase our understanding of fire ignition on electric cooktops by first characterizing their thermal environment and then measuring the ignition and flammability characteristics with different fuels. To cover the different types of electric cooktops, electric coil, ceramic glass, and induction cooktops are selected for the study. Two stove guard models were installed in the test setup in collaboration with their manufacturers' representatives to understand their performance with different cooktop type, pan and fuel combinations. As it was not possible to study several cooktop brands and models from each category, the results cannot represent the whole class of commercial products, and one must be cautious when generalizing our observations.

2. Material and methods

2.1. Cooktops and frying pans

Three models of electric cooktops, one from each category (see Fig. 1), were chosen among the brands and models sold in Finland 2020. Table 1 lists the brands and models, as well as the size and the nominal maximum power of the heating elements at 240 VAC voltage.

Frying pans were used as cookware. Table 2 lists the types and models, and photographs of the pans are shown in Fig. 2. These pans were selected among the products available in one of the largest supermarket chains of Finland. One model was selected for the cast iron and carbon steel categories, and two different models for the aluminum pan, which is the most used frying pan type in Finland. Iron and steel pans were uncoated, but aluminum pans had polytetrafluoroethylene-based coatings. All pans were compatible with both conduction and induction heating, which means that the bottom of the aluminum pans must contain some iron material.

2.2. Fuel materials

The most important test materials are listed in Table 3 and shown in Fig. 3. They were selected to represent cooking oils, butter and additional items that could act as ignition sources on a cooktop. In addition, 23 ignition tests were made using different food items, including sausage (18% fat), minced meat (beef, 10–15% fat), salami pizza, fish fingers, pre-cooked rice, and canned pea soup. All materials were tested without their packaging; in state they appear at room temperature.

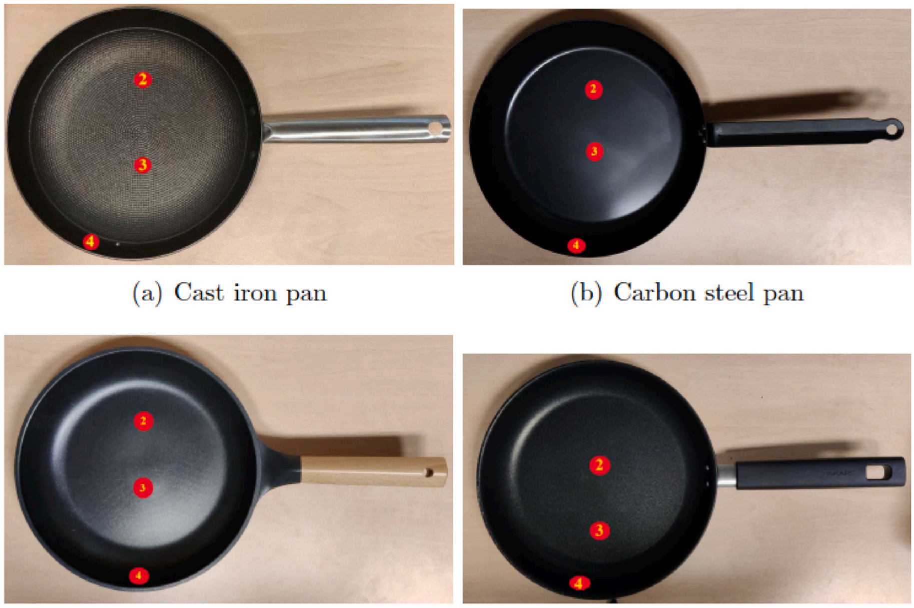
For cooking oils, the amount of oil is known to influence the observed fire behavior. Based on a survey with 291 responses (252 from UK), Spearpoint and Hopkin [16] found out that the most common volume of cooking oil for shallow frying was less than 50 mL and between 300 mL and 1 L for deep frying. As the shallow frying is commonly used in Finnish households, the ignition tests were made with 25- and 50-mL oil volumes. Heat release rates were measured with 50 mL of oil.

2.3. Physical environment

Cooktops were placed next to a 1.3 m wide and 12 mm thick plywood wall within a laboratory hall with >500 m^3 volume. Majority of the ignition tests were performed under a hood with horizontal area of 1.0 × 1.3 m^2, vertical depth of 0.58 m and free height of 0.60 m (Fig. 3). In the heat release rate measurements, a smaller hood (0.60 × 0.41 m^2 and 0.65 m high) was employed to increase the combustion products' concentration in the exhaust stream. To effectively capture all combustion products, we reduced the free height to range of 0.3–0.5 m.

Table 2
Specifications of the frying pans used in the study. Bottom diameter was measured from inside the pan.

Type	Acronym	Brand and model	Bottom diameter (mm)	Weight (kg)
Cast iron	CI	Opa Kenno 28 cm	195	1.66
Carbon steel	CS	Opa Heavy metal 28 cm	224	1.33
Aluminum (A)	AL-A	Myhome kitchen 28 cm	213	0.85
Aluminum (B)	AL-B	Fiskars Hard face 26 cm	209	1.14



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

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

Fig. 2. Placement of thermocouples on frying pans.

Table 3
Most important tested materials in the ignition and HRR experiments.

Material	Brand, size, content	Amount
Oils and butter		
Sunflower oil	Keiju	25 mL/50 mL
Canola oil	Pirkka	25 mL/50 mL
Olive oil	Borges Extra virgin	50 mL
Butter	Valio, fat 80%, salt 1,4%	50 g
Food		
Fish fingers	Pirkka, breaded fish, 7,5% fat, 25 g/finger	75 g
Solid materials		
Paper towel roll	Pirkka, twofold soft tissue paper in a roll	114 g–115 g
PE bags	Pirkka, low-density polyethylene (LDPE) freezer bags	50–60 g
Pizza box	32.5 cm × 32.5 cm × 3.0 cm box made of 1.5 mm thick cardboard	106 g
Potholder	Myhome kitchen, size 22 cm × 22 cm, lining cotton, filling polyester	57 g–60 g

2.4. Measurements and stove guards

Temperatures of the electric coil (EC) and ceramic glass (CG) cooktops' upper surfaces and frying pans were measured using K-type thermocouples (1.0 mm machine-soldered bead). The placement of the thermocouples and ignition items was decided with help of infrared images which were taken using FLIR A655SC camera. Thermocouple T1 was placed outside the heating element, about 30 mm from the element boundary, whereas thermocouples T2, T3, and T4 were placed directly against the heating element (Fig. 1). Light-weight concrete blocks of 20 cm^3 in volume and 42 g in mass were used as mechanical loads to ensure contact. On the frying pans, T2, T3, and T4 were attached by drilling a small hole through the pan and fastening the thermocouple against the pan surface using a screw (Fig. 2). The first 10 cm of the thermocouple wires were aligned with the expected isotherm (element/pan tangent) to minimize heat conduction loss along the wire. Temperatures were recorded with 1.0 s intervals using Keysight DAQ970A data logger and a computer. The cooktop power output was measured using Fluke Norma 4000 power analyzer with announced measurement uncertainty less than 0.2%.

During the ignition and HRR measurement tests, the sample temperatures were measured using three K-type thermocouples with 1.0 mm beads. In oil tests, they were placed within the liquid layer (initial thickness with 50 mL was about 1.5 mm). In solid materials, they were placed on the surface or at different heights within the sample to determine the characteristic material temperature at ignition. One thermocouple was used for measuring gas temperature 60 cm above the cooktop surface. Radiation errors were not corrected.

The heat release rates were measured using the oxygen consumption calorimetry by connecting the smaller hood to the horizontal gas exhaust duct of a cone calorimeter, using a flexible, corrugated aluminum ventilation duct 2.5 m long and 0.12 m in diameter. The HRR measurement applied the CO_2 and CO corrections and was calibrated according to ISO 5660 using a methane burner. The estimated time delay of the HRR signal was about 20 s.

Two commercial stove guards from Safera Oy and Innohome Oy were included in the ignition tests. Both products comply with EN 50615 category B which means they are expected give an alarm and turn off the electrical power before ignition. For these tests, they were modified for not cutting the power, so that the experiment could continue to ignition. Consequently, we were only able to observe whether they reacted before the ignition or not. We could not make conclusions regarding the actual fire prevention performance because ignitions could occur after the power has been cut off.

The stove guards operate by sensing infrared radiation at several wavelengths, thus avoiding the problem of different cookware

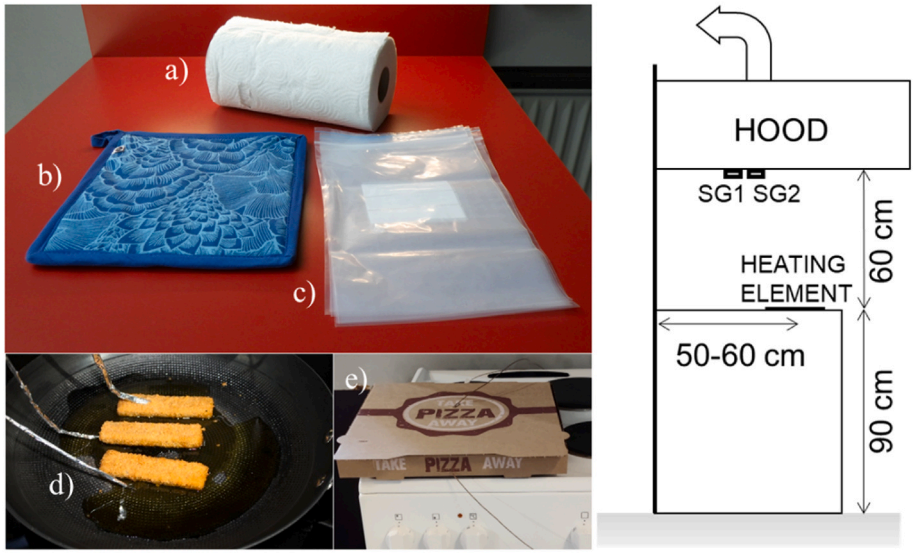


Fig. 3. Fuel items on the left and a schematic side view of the experimental setup on the right. (a = paper towel roll, b = pot holder, c = LDPE bags, d = fish fingers in the pan with thermocouple wires, e = pizza box).

emissivity values. They were installed at 60 cm height above cooktop center with sensor downwards. See SG1 and SG2 in Fig. 3. The cooktop type, width and installation height were specified in the device settings.

2.5. *Test procedures*

Paper towel rolls, potholders, and pizza box were placed directly on the heating elements' hottest points, found with an infrared camera in advance (see Appendix). In general, the highest temperatures were not in the center of the heating element. In 12 tests, pot holders were placed on a the cast iron pan instead of the heating element. PE bags were placed in a 10 × 10 × 2 cm^3 tray made of 2 mm thick steel to prevent uncontrolled flow of melt PE and to limit the HRR into the measurement range of the cone calorimeter gas analyzers. Food items were tested in a frying pan and placed in the pan center.

Materials were kept at room temperature for at least 3 h before the tests. Experiments started with material put on the pan or heating element (at room temperature), data logging was started, power was turned on to the maximum level (not boost), and the time of autoignition was recorded. During the HRR measurement, materials were allowed to burn to completion.

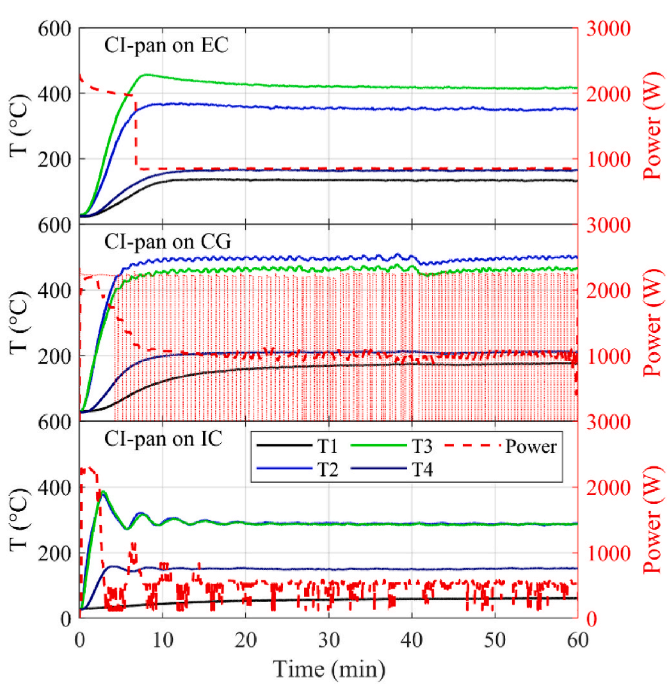


Fig. 4. Surface temperatures and electric power of the electric coil (EC, top figure), ceramic glass (CG, middle figure) and induction (IC, bottom figure) cooktops with cast iron pan and full power settings (see Table 1).

3. Results

3.1. *Thermal characteristics*

Surface temperatures and power consumption were measured at different power levels. Fig. 4 shows the thermocouple temperatures and electric power of the cooktops with cast iron pan, when the power setting is at maximum of each cooktop heating element. As the ceramic glass power signal shows very strong fluctuations between zero and full power, a time averaged version is also shown. Spatial distributions of the steady state temperatures are shown in Appendix as snapshots from the infrared videos.

We observe that the pan temperatures are clearly higher on the electric coil and ceramic glass cooktops than on the induction cooktop. Regarding the heating rate, at the induction cooktop, the peak temperature was reached in few min and with the electric coil in less than 10 min. On ceramic glass highest temperature was recorded after half an hour. Regarding the power control systems, the cooktops are found to have very different designs. While the ceramic glass cooktop power is controlled in time-space by switching the power on and off with 30 or 60 s period and 50% duty cycle, the electric coil power shows abrupt changes but steady and continuous levels between changes. The temporal variation of the ceramic glass cooktop power is reflected in temperature fluctuations of few tens of degrees. The induction cooktop power seems to contain high-frequency fluctuations unresolvable by the 1 s data collection time interval.

The measured peak and steady state surface temperatures with all cooktop-pan combinations are shown in Fig. 5 and the times to reach 300 °C temperature in Fig. 6. The cooktop surface temperatures in Fig. 5 are shown with two power levels, but the pan temperatures correspond to full power only. The peak cooktop surface temperatures were

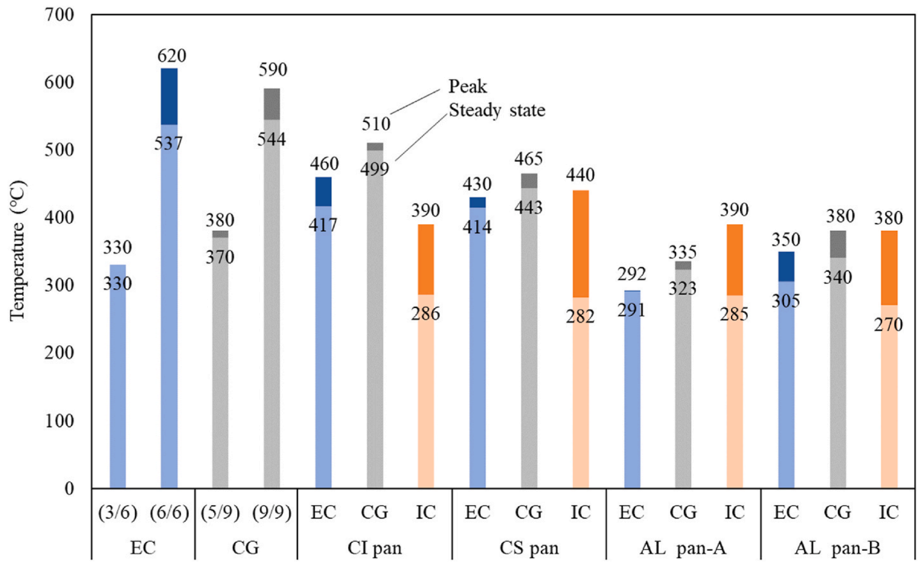


Fig. 5. Measured peak and steady state temperatures of the cooktops and pans. Results without pans at two different power settings. Results with pans at full power only.

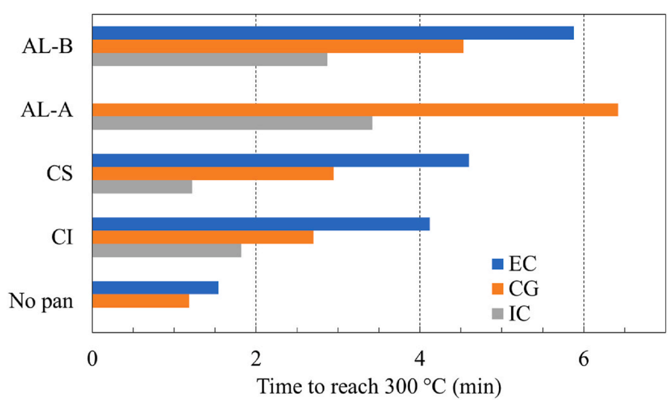


Fig. 6. Times to reach 300 °C temperature with different cooktop/pan -combinations.

80–160 °C higher than the highest pan temperatures, quantifying the role of the heat conduction limitations and heat losses. The heat conduction -based cooktops (EC and CG) produced significantly higher temperatures with cast iron (CI) and carbon steel (CS) pans than with the aluminum pans. Induction cooktop, in turn, produced very similar temperatures with all the pan types, but the difference between the peak temperatures (380–440 °C) and steady state (270–286 °C) is greatest among the cooktops. These results indicate that both the cooktop and pan types influence the heating and, therefore, the likelihood of material ignitions.

In addition to the well-known benefit of the induction cooktop, i.e. the low likelihood of ignition in the absence of cooking hardware, the current measurements revealed additional safety-related characteristics: The maximum peak temperatures and steady-state temperatures were lower than on the heat conduction -based cooktops, which may be caused by faster control system and lower thermal inertia. On the other hand, induction cooktop heated up the pans faster (Fig. 6). With small amounts of flammable material, like cooking oil, faster heating increases the likelihood of ignition because it is easier to reach the flammable vapor concentration before the material is fully consumed.

3.2. Ignition probabilities and times

Due to the large parameter space and the need to perform repeated tests, a full experimental design could not be implemented. In cases where the first test indicated very unlikely ignition, further tests on the same combination were often abandoned. Also, the tests cannot be considered a random sample either. Therefore, the current results must be seen as indicative, especially regarding the probability estimates.

Table 4
Indicative ignition probabilities with 95% confidence intervals (Student's t-test) and ignition times and temperatures of oils and butter. (SD = standard deviation). An empty cell for fuel, cooktop or pan means that all configurations are included.

Fuel	Fuel2	Cooktop	Pan	N	Ignition probability			t_{ign} (s)		T_{ign} (°C)	
					n_{ign}	p_{ign}	95% CI	Mean	SD	Mean	SD
				121	42	0.35	0.09	325	100		
	None			62	27	0.44	0.13	309	81		
	Fish			59	15	0.25	0.12	355	124		
		EC		17	1	0.06	–	426	–		
		CG		69	28	0.41	0.12	372	79		
		IC		35	13	0.37	0.18	218	39		
		IC	CI	24	11	0.46	0.23	229	30		
		IC	CS	10	2	0.20	1.61	157	5		
		IC	AL	1	0	0.00	–	–	–		
Sunflower oil		CG	CI	9	5	0.56	0.46	321	15	392	29
Canola oil		CG	CI	8	7	0.88	0.29	311	24	385	27
Olive oil		CG	CI	6	4	0.67	0.61	401	95	420	39
Butter		CG	CI	19	4	0.21	0.30	335	50	429	18

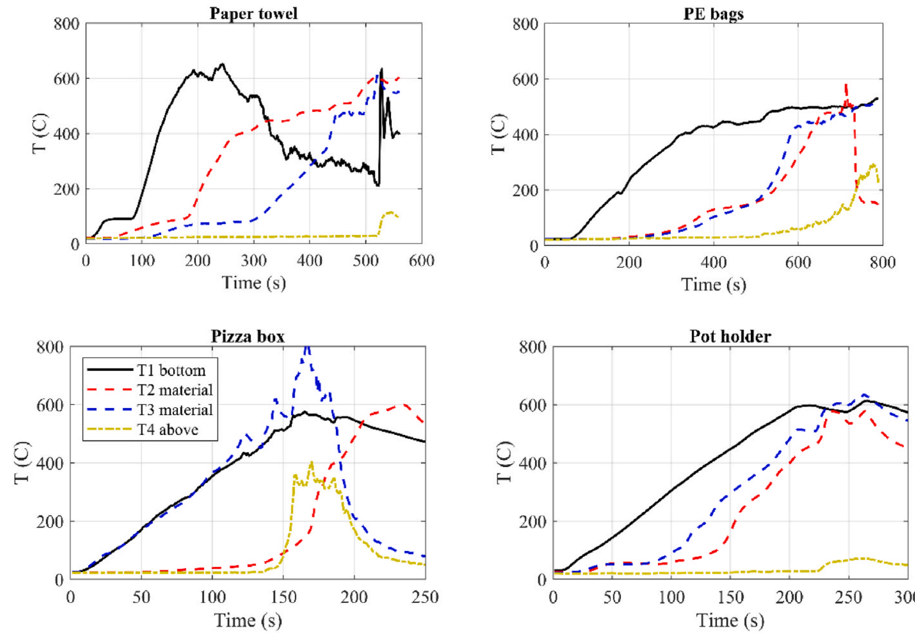


Fig. 7. Temperature measurements in individual solid fuel ignition tests on CG cooktop. The moment of ignition is when T4 (above the fuel) shows a sudden increase.

More systematic test series is needed for reliable statistics.

Altogether, 121 tests were made with different oil/butter-cooktop-pan -combinations, including the dedicated ignition tests and the HRR measurements. Estimates of the auto-ignition probabilities were calculated as proportions of the tests, where flames were observed, among all tests of a specific category, $p_{ign} = n_{ign}/N$. Table 4 shows these probability estimates with corresponding 95% confidence intervals for oils and butter. The results are shown for different categories and sub-categories, so that when the table cell is empty, it means including all the possible combinations. For example, out of the 121 oil/butter tests, in 79 tests, the oil/butter was evaporated and fully consumed without ignition, but 42 tests had ignition ($p_{ign} = 0.35 \pm 0.09$). These 121 tests then contain two sub-categories: tests with just oil/butter ($p_{ign} = 0.44 \pm 0.13$) and tests with oil/butter and fish fingers (0.25 ± 0.12). We see that fish fingers seem to have prevented some of the ignitions. Ceramic glass and induction cooktops had ignition probabilities close to 0.4, but on the electric coil cooktop, only one ignition occurred, leading to very low and unreliable probability estimate. As 99 of the 121 oil/butter tests were done using the cast iron pan, we cannot make conclusions about the role of the pans in ignition.

The difference between the oils and butter can be studied by looking at the sub-set of tests with ceramic glass cooktop and cast iron pan: canola oil ignited most often ($p_{ign} = 0.88 \pm 0.29$), sunflower and olive oil were quite similar with ignition probabilities slightly above 50%, and butter seemed to ignite least frequently (0.21 ± 0.30). In these categories, the small sample size reduces the confidence.

Table 4 also shows the means and standard deviations of the ignition times and material temperatures just before the ignition, calculated from the tests with ignition. On average, ignitions occurred in 325 ± 100 s. Inclusion of the fish fingers did not change the ignition times significantly, but the cooktop type appeared to play a role: Ignitions happened much faster on the induction cooktop (218 ± 39 s) than on the ceramic glass cooktop (372 ± 39 s). This may explain why their ignition likelihood values are similar despite the lower temperatures of the induction cooktop; fast heating enables ignition before oil is fully consumed by evaporation. This factor may increase the likelihood of ignition with small oil amounts.

The observed oil auto-ignition times can be compared with the study of Chen et al. [11] who studied the ignition of corn oil using a 14 cm heater coil and reported a linear correlation between the oil mass and auto-ignition time, indicating ignition times of 530 s and 630 s, for 25 mL and 50 mL oil volumes. The current ignition times of, for example canola oil (311 ± 24 s), are much shorter although the fire points of the two oils differ with only few degrees (355–367 °C for canola vs. 362–382 °C for corn oil [11]). The induction cooktop ignition times, in turn, are consistent with the results of Wong et al. [19] who recorded 200 s ignition time for 50 mL of peanut oil on an induction cooktop. Comparing the sunflower oil's ignition temperature (392 ± 29 °C) against a reported autoignition temperature 345 °C [9] indicates that the ignitions in our experiments have occurred at higher temperature than what can be observed in experiments with thicker oil layers and slower heating. It seems that it is difficult to assess the auto-ignition time differences between oil types when the heating systems are different.

For the solid items, 61 tests were performed with estimated ignition probability of 0.80 ± 0.10 and mean ignition time of 378 ± 228 s. We can observe that the solid items ignited with higher probability but later than the oils and butter. In 12 of the 24 pot holder tests, pot holder was placed on a CI pan instead of the cooktop surface directly. Only two of these tests led to ignition. Ignoring the tests with a pan, the solid item ignition probabilities would lie between 0.92 and 1.0.

Minced meat, salami pizza, fish fingers, sausage, rice and pea soup did not ignite. No further details are reported for these materials.

The solid ignition times contain great variability so that pizza box and pot holders ignited most rapidly and paper towel and PE bags with longest times. Material temperatures at the time of ignition, in turn, were significantly higher than the corresponding oil temperatures. Understanding the solid fuel ignitions requires closer look at the measured temperature histories that were measured by placing thermocouples between the cooktop and the material, and inside the material. Examples of solid material temperatures are shown in Fig. 7. Solid black lines (T1) show the temperature between the cooktop surface and sample, dashed lines (T2, T3) show the thermocouple readings inside the sample, and T4 shows the gas temperature 10 cm above the sample. In the paper towel roll, thermocouples T2-T3 were penetrated inside the roll from the

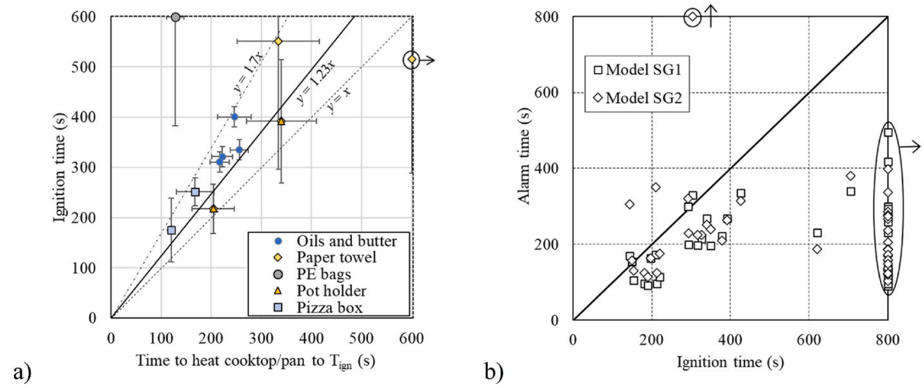


Fig. 8. a) Comparison of ignition times vs. the times when the empty cooktop or pan would reach the observed ignition temperature. The arrow indicates that the CG cooktop did not reach T_{ign}. b) Comparison of ignition times and alarm times of stove guards. The arrow to right indicates tests that did not ignite but an alarm was given. The datapoint with upwards arrow indicates a case where ignition occurred but alarm was not given.

Table 5
Indicative ignition probabilities and their 95% confidence intervals (Student's t-test) and ignition times and temperatures of solid items on EC and CG cooktops. An empty cell means all configurations.

Fuel	Pan	N	Ignition probability			t_{ign} (s)		T_{ign} (°C)	
			n_{ign}	p_{ign}	95% CI	Mean	SD	Mean	SD
		61	49	0.80	0.10	378	228	–	–
Paper towel	None	15	14	0.93	0.14	528	228	603	57
PE bags	None	8	8	1.00	0.00	600	216	438	37
Pizza box	None	14	14	1.00	0.00	203	64	410	49
Pot holder		24	13	0.54	0.22	269	112	–	–
Pot holder	None	12	11	0.92	0.18	288	112	594	66
Pot holder	CI	12	2	0.17	1.4	166	27	–	–

direction of the roll end at heights corresponding to one fourth and half of the roll diameter. Results show an upwards propagation of a smoldering front. The ignition occurred when the smoldering had reached about midway of the roll. The PE bags in turn melted before they ignited at 517 s, and temperatures T2 and T3 remained well below the tray temperature T1. In the pizza box, one of the internal bottom cardboard thermocouples follows closely the bottom temperature T1 but exceeds that when flaming starts inside the box. In the pot holder, T2 and T3 were placed between the top lining and the filling. They follow the bottom temperature with about 100 s delay, reaching a temperature that exceeds the maximum ceramic glass (CG) cooktop temperature (Fig. 5) just before ignition. These results illustrate that the processes like smoldering and melting contribute to the solid fuel ignition process, thus preventing us from formulating simple safety criteria on the cooktop temperatures.

The role of the material heating and degradation processes in the ignition is quantified in Fig. 8a by plotting the observed ignition times (mean ± one standard deviation) against the 'heating times', i.e. the times required for the cooktop to reach the material's 'ignition temperature' (Tables 4 and 5). Different data points for a single material correspond to electric coil and ceramic glass cooktops, and the horizontal error bars indicate the time spans resulting from the temperature standard deviations. The vertical difference between a data point and the '$y = x$' -line can now be interpreted as an 'ignition delay'. All the ignition delays, except the PE bag, are less than 1.7 times the 'heating time', and a linear regression with zero intercept gives the following linear model: *ignition time* = 1.23 × *heating time*. The ignition time thus mainly depends on how quickly the cooktop heats up. Material-related processes are responsible for about one fifth of the ignition time. The outlier behavior of the PE bags may be attributed to the use of the relatively heavy steel tray where the bags were placed. Faster ignition – and much more severe fires – might result from placing the bags directly on the cooktop surface.

One interesting feature of Fig. 8a is that pot holders (both electric coil and ceramic glass) and paper towels (on ceramic glass) ignited before the cooktop had reached the nominal ignition temperature. These ignitions were thus accelerated by the smoldering process, which was also visually observed in the experiments.

The potential of the stove guards to prevent the studied cooktop fires is studied in Fig. 8b by plotting the alarm times against the ignition times in 44 tests. All the fuel types except the PE bags were included in the data. The group of data on the right edge of the figure were those tests where an alarm was given but no ignition occurred. Stove guards alarmed before the ignition occurred in almost all cases. The cases with late alarm (or no alarm at all, in one case) were either pizza box or pot holder fires, where the view of the detecting elements to the heated area was at least partially prevented. As the operating principle of these stove guards was based on thermal radiation (overheating) detection, they may fail if the heating area is hidden. For oils and other fuels, which closely resemble the EN 50615 test scenarios, these safety devices were found to provide highly reliable means for detecting overheating and potential for preventing ignition. Note that the ignition prevention was not tested – only the potential. Further research with different fuels and cooktops is needed to quantify how early the detection must occur for preventing the ignitions.

3.3. Heat release rates

Heat release rates were measured with electric coil and ceramic glass cooktops for pizza box, paper towel, pot holder, PE bags (Fig. 9) and oils/butter (Fig. 10). Oil tests with fish fingers are shown in a separate figure. As the oils, butter and the PE bags burn in liquid state, their HRR

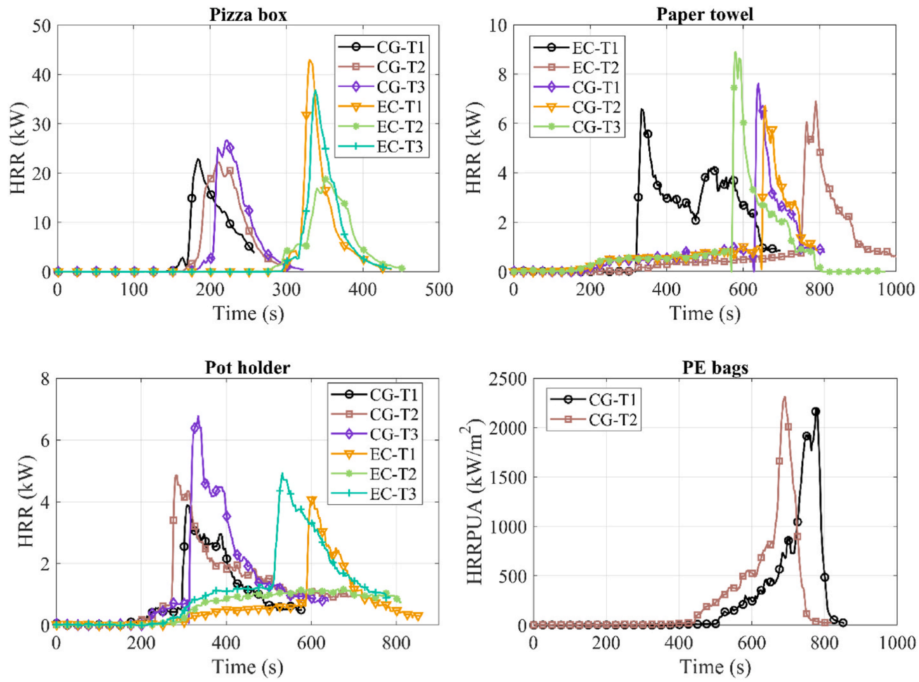


Fig. 9. Measured heat release rates of solid items. As the PE bags melt before they ignite, their HRR were normalized by the tray area. T1 – T3 refer to repeats.

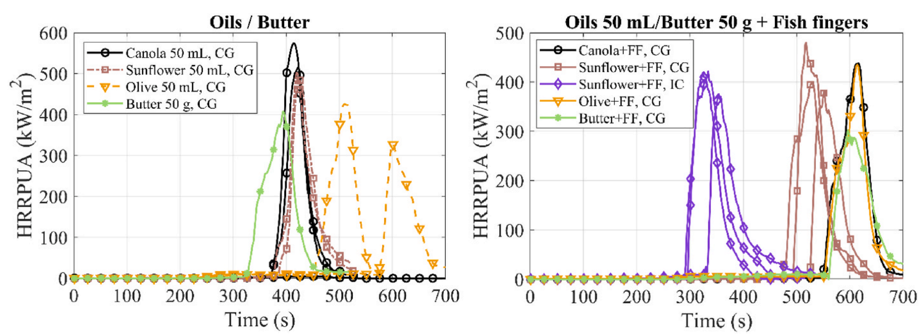


Fig. 10. Measured heat release rates per fuel (pan) area of oils (left) and oils + fish fingers (right).

are proportional to the burning area. Therefore, these results were normalized with the pan/tray area and presented in the form of heat release rate per unit area (HRRPUA). Three repeated measurements were done in most cases. Individual repeats of the solid items are shown with different line types, but for oil, repeated tests are shown with identical lines for the sake of clarity.

Both pizza box and pot holders show faster ignitions on the ceramic glass cooktop than on the electric coil cooktop. For pizza boxes, the earlier ignition also correlates with lower HRR, while the same cannot be observed for the other solid fuels. Paper towel ignitions are widely scattered but the HRR curves have very similar shapes with relatively long smoldering period, followed by a sharp HRR peak and burn duration of about 200 s. In general, pizza box peak HRR were much higher than those of the other solids.

PE bags burned at increasing rate after ignition and showed peaks above 2000 kW/m^2 just before burnout. A melting and igniting pool of polyethylene, or any other thermoplastic, can lead to severe consequences in a limited space like kitchen. Storing plastic items so that they can be melted by a hot cooktop element must therefore be considered as one of the greatest contributors to kitchen fire risk.

The durations of the oil and butter fires (Fig. 10) were order of one hundred seconds, and they showed a single peak between 330 and 600 kW/m^2 in approximately middle of the burning period. On average, adding fish fingers reduced the peak HRR but the total amount of energy was not changed. Also, different ignition times of the sunflower oils + fish fingers on CG and IC cooktops did not seem to affect the peak HRR.

Chen et al. [11] measured a 14.7 kW ± 26% peak HRR for 50 g of corn oil on electric coil heating element, corresponding to 1990 kW/m^2. According to their results, the original mass of oil had a great influence on the observed HRR. For example, with 20 g mass, the peak HRR was only 7.9 kW ± 15%, i.e. 1070 ± 160 kW/m^2. In the current research, the peak HRRPUA values range between 300 and 600 kW/m^2. One reason for the different results can be related the pan size; our pans were much larger and fuel layers thinner despite the similar fuel masses. Consequently, our fire durations were short, order of 100 s, and the peak HRR values were achieved quickly, 20–40 s, after ignition. In the experiments of Chen et al. [11], the fire durations were longer (150–250 s) and comprised of two stages: an initial, linearly growing HRR and a boiling regime. The peak HRR values in their tests were observed 50–120 s after ignition.

For assessing the capability of the investigated cooktop fires to ignite kitchen structures, the measured peak HRR values were used to calculate the fire plume temperatures 0.6 m above the cooktop surface, i.e. at the height of a typical kitchen closet, using the plume model of McCaffrey [22]. For oils and PE bags, the actual measured HRR values from frying pans and 10 × 10 cm^2 were used. According to the calculation, pizza box, oils, butter and PE bags could lead to temperatures above 400 °C. Measured gas temperatures for olive oil, butter and PE bags were 366 °C, 200 °C and 286 °C, i.e. somewhat lower. Burning potholder or paper towel with calculated plume temperatures between 145 °C and 240 °C would be less likely to ignite structures. The melting thermoplastic with high likelihood of ignition and a possibility of large pool fire, i.e. high HRR, was found to correspond to the highest risk of fire spread and burn injuries. Cooking oils represent a well-known fire hazard in kitchens, but the consequences associated with oil fires may be smaller than those by burning plastics due to the confined area of the cookware.

4. Conclusions

Based on the measured surface temperatures of three electric cooktops and four different frying pans, we can conclude that, in addition to the inherent safety of the induction cooktops when ferromagnetic cookware or other materials are not present, highest peak temperatures and the steady state temperatures on the induction cooktop were lower than on the other types. Naturally, generalizing this observation for the other brands and models requires further studies. On the other hand, induction cooktop was found to heat up the cookware much faster, which led to faster ignition of flammable materials: Oils and butter, for example, ignited in 218 ± 39 s on the induction cooktop, while 372 ± 79 s were required on the glass ceramic cooktop.

The estimated overall ignition probability of cooking oils (25–50 mL) and butter (50 g) was 0.44 ± 0.13 but adding fish fingers reduced the probability to 0.25 ± 0.12. Among the three oil types, canola oil ignited with highest probability (0.88 ± 0.29). These ignition probabilities must, however, be considered only indicative and biased towards high probabilities, as the test campaign was neither randomized nor fully systematic. On average, oil/oil + fish ignitions took place in 325 ± 100 s, being faster on the induction cooktop than on the ceramic glass cooktop. Adding food to the pan was found to delay the ignitions.

Solid items left on the heating element ignited with an estimated probability of 0.80 ± 0.10 in 378 ± 228 s and at significantly higher temperatures than the oils. Pizza box and pot holders ignited most rapidly and paper towel and PE bags with longest times. Great variability was found within and between the ignition times of the current and literature studies. They are presumably due to the different heating rates. Indeed, comparing the ignition times against the cooktop heating times showed that the speed of the cooktop is the main contributing factor, and the material -related processes were found to delay the ignition by 23% of the heating time. Porous materials form a special group because the exothermic smoldering can increase the material temperature above the cooktop temperature, making the ignition time unpredictable in practice.

The heat release rates of cooking oils, butter or solid items were measured and reported. Oil peak heat release rates per pan area were in the range 300–600 kW/m^2 which led to HRR of 20–35 kW and flames capable of igniting kitchen structures. LDPE bags on a hot cooktop were found to have potential for the highest risk because they ignited with high likelihood, produced normalized peak HRR greater than 2000 kW/m^2, and because they can melt and spread over a large area. Of the other solid items, pizza boxes produced peak HRR between 20 and 40 kW, but pot holders and paper towels remained below 10 kW in power.

Finally, the stove guards activated consistently before the ignition occurred, except for the pizza box and pot holders. The thermally insulating bodies of these items prevented the radiation sensors from detecting the high-temperature region of the cooktop. Although the actual ignition prevention was not measured in this study, we can conclude that, in combination with induction cooktops, stove guards should provide an effective protection against cooktop fires. Further development of the EN 50615 standard is, however, necessary to ensure that fires originating from auxiliary materials can also be prevented.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT by OpenAI in order to check and improve English language expressions. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix. Supplementary material: Infrared images of cooktops and pans

Infrared videos were recorded using FLIR A655SC infrared camera, placed directly above the heated element. Fig. 11 shows snapshots from the videos during steady state. The observed peak temperatures may differ from the thermocouple readings because the surface emissivities, used by the analysis software, were not calibrated.

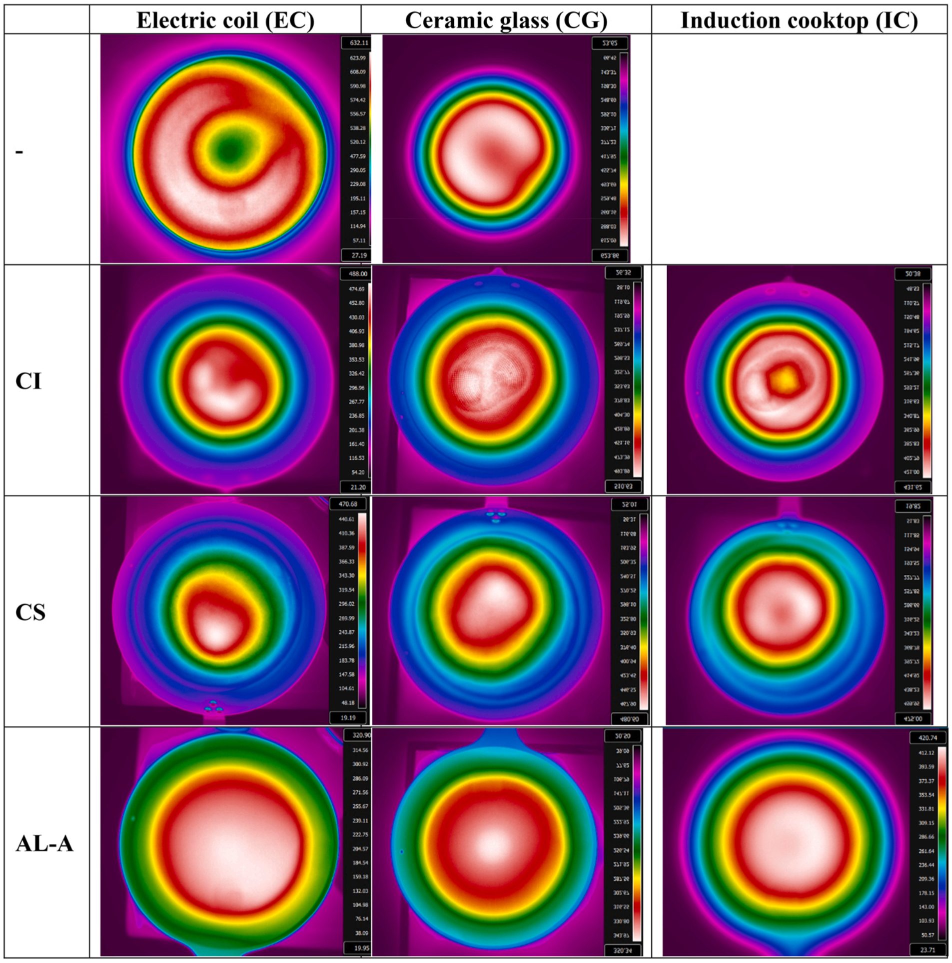

Fig. 11. Infrared images of the cooktop and pan temperature distribution during steady state.

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