Experimental analysis of required ignition times of unattended incidents in kitchens

Alonso A.[1,*], Alvear D.[1], Lázaro M.[1]

GIDAI group, Universidad de Cantabria, Cantabria, Spain.
**Corresponding author's email: alonsoia@unican.es*

ABSTRACT

Kitchen fires represent a significant portion of residential fire incidents worldwide, with statistical data identifying unattended cooking as a leading cause. These fires often originate from oil or grease in cookware, with heat and smoke from the initial fire plume igniting nearby secondary items. This progression can escalate into full-scale fire involvement, particularly under ventilation conditions that promote fire growth. This study investigates the behaviour of unattended kitchen fires through a series of full-scale experiments, focusing on the duration of the primary ignition source and the potential ignition times of secondary items. A fully furnished kitchen mock-up was constructed, and thermocouples were installed on various surfaces to record temperature data. Twelve tests were conducted using sunflower oil in quantities ranging from 50 to 300 ml as the ignition source. Regardless of the oil quantity, temperatures rose rapidly at the start of the flame period, peaking within two minutes. Larger oil quantities produced higher peak temperatures and extended flame durations. Thermal effects were concentrated on the upper backsplash, under the range hood, and along the lateral surfaces of adjacent cabinets.

KEYWORDS: cooking oil, full-scale fire tests, fire behaviour.

INTRODUCTION

Kitchen fires are a common and dangerous occurrence, representing a significant fraction of residential fires globally [1-3]. Cooking activities are the primary contributor, accounting for nearly 50% of all residential fire incidents [1]. Reports and database from fire services indicate that cooking materials, are the most frequently ignited elements in these fires, responsible for up to 30% of cases [1, 3]. Among the various causes, unattended cooking stands out as the leading factor, contributing to 31% of incidents [2]. This risk is particularly critical during frying, a cooking technique that involves temperatures higher than 160°C [4]. Distractions during frying can lead to the rapid overheating of combustible materials, ultimately resulting in ignition, and the potential for secondary items to catch fire, significantly increasing the likelihood of full-scale involvement of nearby furniture and kitchen elements.

To improve kitchen safety and design safer cooking environments, it is crucial to understand the ignition properties of cooking materials and their interactions with surrounding objects. Previous studies in the literature can be classified into two areas: i) the spread and behavior of flames within the kitchen following the ignition of cooking materials [5-7] and ii) the thermal properties and combustion characteristics of flammable materials [8-10]. These studies provide valuable experimental insights, including data on temperature profiles, heat radiation, heating rates, and the identification of critical conditions under which ignition occurs. Nonetheless, their primary focus is not to measure the effect of heat from the primary ignition source on surrounding objects. The present study aims to measure and compare the energy released during the ignition of specific quantities of cooking oil (the primary ignition source), its duration, and the resulting temperatures on surrounding elements (secondary items), along with their required ignition times.

To achieve this, a series of full-scale tests were conducted in a fully furnished mock-up kitchen. It is important to note that while laboratory tests provide highly valuable data, reproducing a fire on a real scale is often constrained by the destructive nature of such experiments. This limitation makes full- scale testing a less common yet indispensable approach for obtaining practical data in the field of fire safety. To address this challenge, the initial quantity of cooking oil was progressively increased from smaller to larger amounts. This methodology enabled up to 12 tests to be performed with minimal damage to the mock-up, except in cases involving the largest oil quantities. Measurements included the energy released by the fire and temperatures recorded at various locations, focusing primary on areas surrounding the cooking zone.

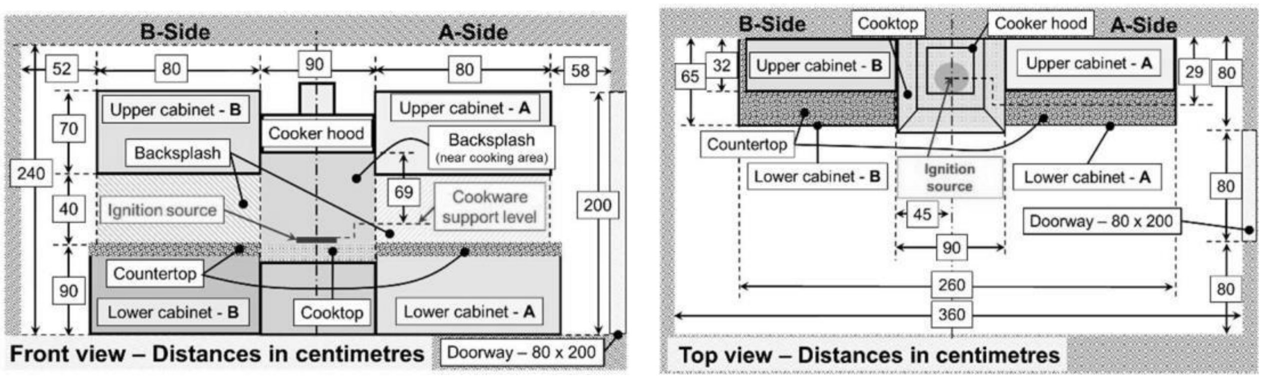
METHODOLOGY

Based on previous studies [5-10], several key physical factors influencing kitchen fires can be identified, including: i) properties of the primary ignition source (e.g., burning rate and energy released by the combustible material); ii) properties of secondary fuels (e.g., quantity, orientation, spacing, surface area of obstacles, and their thermal properties); and iii) enclosure effects (e.g., room temperature, humidity, and ventilation). Since modifying the configuration of a full-scale kitchen setup requires significant effort, and in some cases may be unfeasible, a single test configuration was established. In this configuration, only the initial amount of cooking oil was varied across the different tests.

The test preparation process was standardized for all experiments. Pure and unused sunflower oil was poured into a 20 cm diameter stainless steel pot and heated until it reached its autoignition temperature. The pot was placed at the center position beneath the cooker hood. Initial oil quantities tested were 50 ml, 100 ml, 150 ml, 200 ml, and 300 ml, with each quantity tested twice (expect for 200 ml and 300 ml, which were tested 3 times). It is important to note that, due to frothing phenomenon that occurs when the oil reaches high temperatures [7], testing quantities larger than 300 ml was deemed unsafe under the given conditions.

Full-scale kitchen set-up

The fully furnished kitchen mock-up was set up in a room measuring 360 cm in length, 240 cm in width, and 240 cm in height. The room had a single doorway, measuring 80 cm in width and 200 cm in heigh, located on one side. The kitchen configuration followed a single-wall layout, including two upper cabinets, two lower cabinets, a countertop, a backsplash, a cooktop, an extractor hood, and an oven. The dimensions and placement of these components are illustrated in Fig. 1, whereas the materials and thicknesses are detailed in Table 1.



(a) (b)

Fig. 1. Dimensions (in cm) and location of the elements of the kitchen mock-up. (a) Front view; (b) Top view.

Table 1. Materials and thicknesses of the elements in the kitchen mock-up.

Element	Material	Thickness (mm)
Walls	Gypusm board	15,000
Countertop	Medium Density Fiberboard (MDF)	3,000
Backsplash (near cooktop)	Steel	0,075
Backsplash	Medium Density Fiberboard (MDF)	0,500
Upper cabinets	Medium Density Fiberboard (MDF)	1,500
Lower cabinets	Medium Density Fiberboard (MDF)	1,600
Countertop	Medium Density Fiberboard (MDF)	3,000

Medium density fibreboard (MDF) panels were covered by a sheet of melamine (≈ 1 mm thick), a composite material commonly used in furniture.

Data collection

Since the primary aim of this work is to study the potential ignition of furniture items during a kitchen fire. Special attention was given to measuring the temperatures of various elements, as the ignition of condensed fuel involves three key processes: the gasification of the fuel, the mixing of fuel vapor with an oxidizer, and the ignition of the resulting mixture. Each of these process occurs over a specific timescale. Among them, the gasification time for solid fuels is significantly longer than the mixing and chemical reaction times. Therefore, in this study, the ignition time for solid fuels is defined as the gasification (pyrolysis) time.

To support this analysis, a detailed temperature monitoring plan was developed for the various elements (Fig. 1). Two distinct temperature types were measured: gas phase and solid phase. Gas phase temperatures represent the temperature of the gaseous layer surrounding the object, while solid phase temperatures indicate the temperature of the material in direct contact with the thermocouple. Due to technical limitations in attaching thermocouples, solid-phase temperature measurements were limited to selected elements, namely the cabinets and the cooker hood. Figure 2 depicts the positioning of the thermocouples, while Table 2 details their placement on the elements for the A-side. The arrangement was symmetrical with respect to the y-axis, ensuring uniform data collection across the experimental setup.

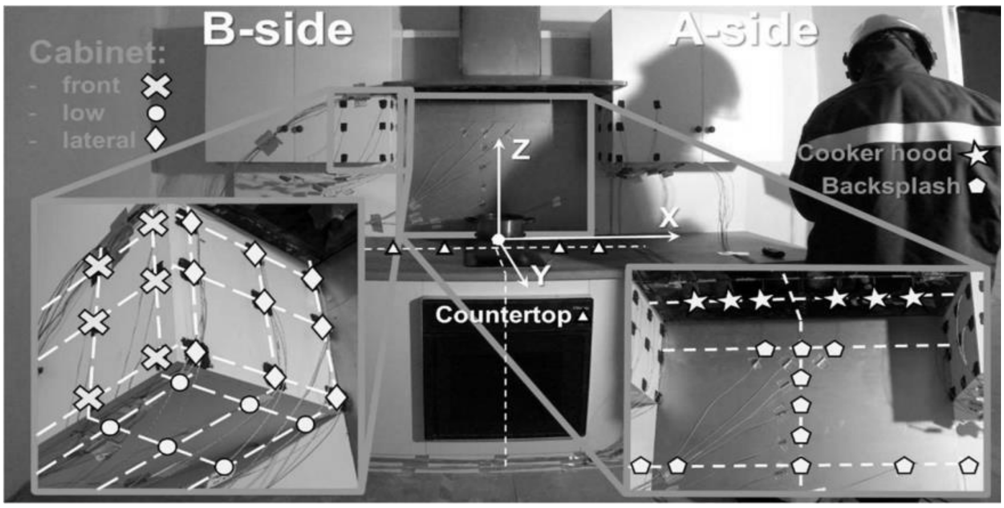


Fig. 2. Location of the thermocouples in the kitchen mock-up.

Table 2. Positioning of thermocoples in A-Side (distances in centimetres).

Element	Symbol	Number	x-axis	y- axis	z-axis
Countertop	Triangle	2	20, 42	0	0
Backsplash	Pentagon	3	10, 34, 46	-29	20, 60
Backsplash (axis of simmetry)	Pentagon	5	0	-29	20, 30, 40, 50, 60
Cooker hood	Star	3	10, 20, 30	0	65
Cabinet low face	Circle	6	48, 64	-28, -15, -1	40
Cabinet front face	Cross	6	48, 64	3	42, 56, 66
Cabinet lateral face	Diamond	9	45	-28, -15, -1	42, 56, 66

It should be noted that on the backsplash, all the devices were placed on the metallic area except for two. These two devices were located at a height of 20 cm and at a distance of 46 cm from the axis of symmetry, positioned on the wooden section.

Since the kitchen was constructed within the fire test room of the Room Corner Test (RCT) apparatus (ISO 9705 [11]), the smoke generated during the tests was collected for analysis. The energy released (Heat Release Rate-HRR) by the ignition source and the potential ignition of the kitchen elements was evaluated using the principles of oxygen consumption calorimetry [12], as described by Eq. (1).

$$\dot{q} = E\left[\frac{X_{O_2}^{A^0} - X_{O_2}^{A}}{1 - X_{O_2}^{A}}\right]\dot{m}_a \frac{M_{O_2}}{M_a}\left(1 - X_{H_2O}^{0} - X_{CO_2}^{0}\right) \tag{1}$$

where: $\dot{q}$ (kW) is the rate of heat released; E is the heat released per unit mass of oxygen (13,1 MJ/kg of O_2), M_a and M_{O_2} are the molecular weights of the air and oxygen respectively (kg/mol);$\dot{m}_a$ is the mass flow rate of the incoming air (kg/s); $X_{O_2}^{A^0}$, $X_{H_2O}^{0}$ and $X_{CO_2}^{0}$ are the mole fraction of O_2, H_2O and CO_2 in the incoming air respectively (-).

This approach enables correlating the initial amount of combustible material, the energy released during its ignition, and its effects on the surrounding elements.

RESULTS

This section is organized into three parts: i) a qualitative description of the sequence of events during the tests; ii) the results of parameters related with energy released, and iii) the temperatures recorded inside the compartment.

The next sequence for T7 (200 ml) serves as a representative example for all tests, with variations in the timing of events, except for the 50 ml tests as the flame did not reach the cooker hood. The sequence (Fig.3) of events is as follows: at t ≈ 440 s, autoignition of oil took place; by t ≈ 470 s (30 seconds after autoignition), its flame exhibited a moderate rate of growth. At t = 475 s, the flame reached the cooker hood. By t ≈ 490 s, the vertical flame structure is affected by the hood. Then, the highest temperatures were reached at t ≈ 522 s, and by t ≈ 559 s, the flame ceased direct contact with the hood. Finally, at t = 590 s (150 seconds after the autoignition), the flame extinguished by fuel consumption.

A key observation across all tests (except T1 and T2) is that the flame exhibited a gradual increase in size during the initial 30 seconds following autoignition. After this period, a noticeable acceleration in growth occurred, until reaching its height peak. The flames typically reached the hood approximately 30 seconds after autoignition, spreading rapidly across the bottom of the hood from the initial point of impingement. When the vertical extent of the buoyant plume was limited by the hood, creating a gas layer beneath that surface. Then the intermitent zone of the flame was also deflected horizontally with a considerable flame extension.

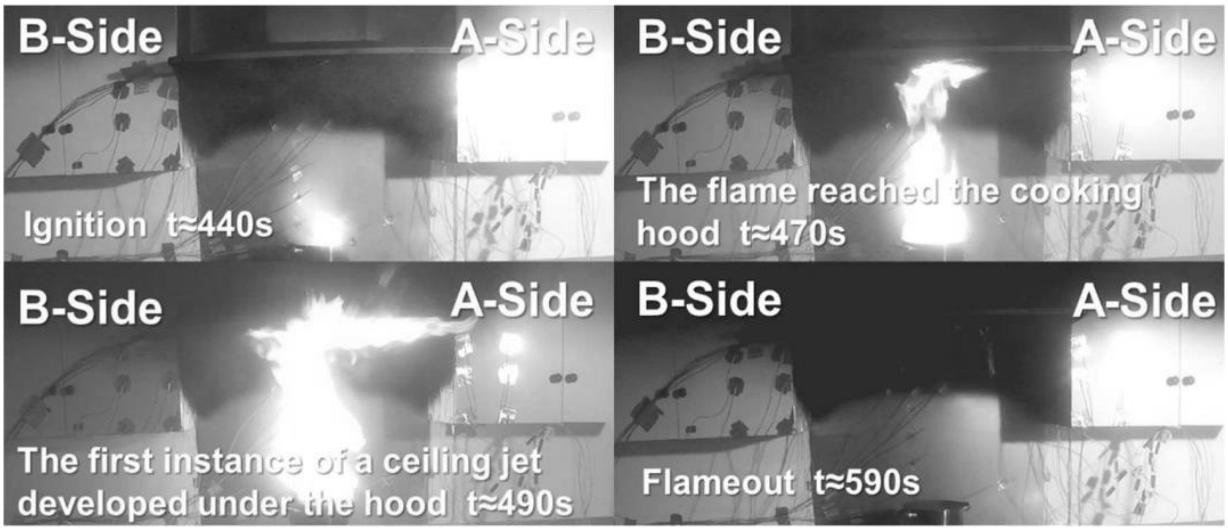


Fig. 3. Evolution of the fire in T7 (200 ml) and key moments.

Next Figure 4 and Table 3 present the energy values measeured during each test.

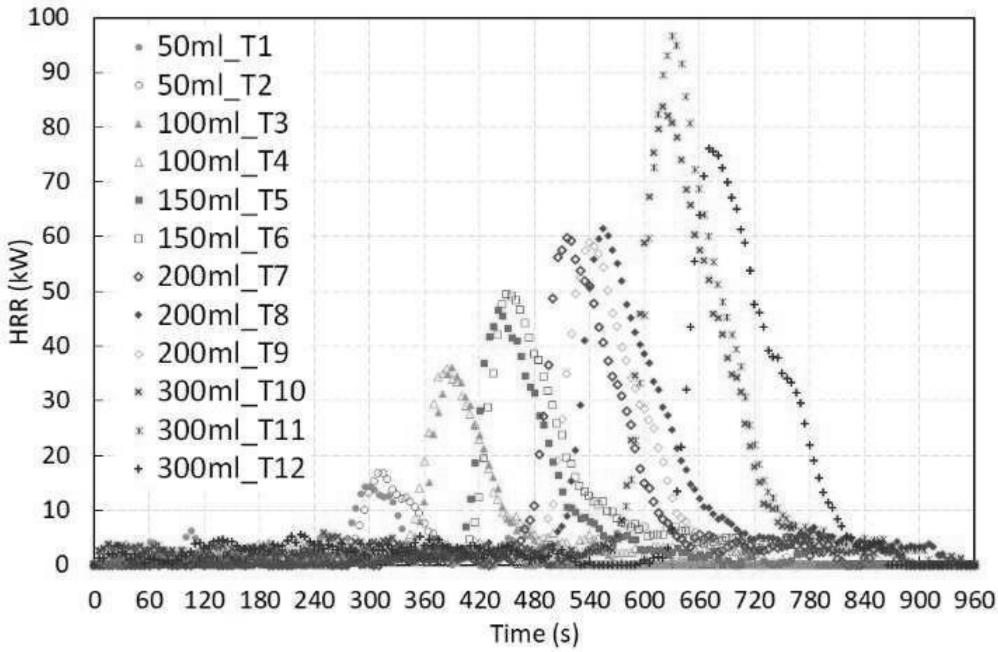


Fig. 4. HRR curves measured from tests.

The HRR curves show that larger initial oil volumes result in higher peak HRR values and longer combustion periods. The 50 ml tests exhibit consistently low HRR values (14,3 ÷ 16,8 kW), while the 300 ml tests reach peaks of approximately 90 kW, with significantly extended flamming times. Intermediate volumes, such as 100 ml, 150 ml, and 200 ml, show progressively higher peaks and longer durations as the oil volume increases. The time to ignition and growth phases vary between tests, with larger oil volumes displaying a delayed but more pronounced rise in HRR.

Regarding the Total Heat Released (THR), the values range from 1,2 MJ for the smallest quantity to 9,5 MJ for the largest.

Similarly, the flaming period lengthens with larger oil quantities. T1 and T2, with the smallest oil amounts, have a flaming duration of 95 seconds, whereas Tests T10, T11, and T12, with the largest oil quantities, show flaming periods ranging from 170 to 200 seconds. This extension of the flaming period reflects the prolonged combustion phase due to the increased initial fuel load.

Table 3. Combustion characteristics of test.

Parameter / Test	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12
Initial quantity (ml)	50	50	100	100	150	150	200	200	200	300	300	300
Time to ignition (s)	230	255	335	330	390	395	440	470	480	560	545	605
Flaming period (s)	95	95	110	110	120	135	145	150	150	170	185	200
HRR peak (kW)	14,3	16,8	36,2	35,9	46,7	49,5	59,8	61,5	59,0	83,8	96,6	76,1
Total heat released (MJ)	1,2	1,2	2,8	3,4	4,3	5,5	6,0	6,8	5,5	8,4	9,5	7,9

As far as the thermal effects on the kitchen elements are concerned, they were particularly significant in specific areas, such as the upper section of the metallic backsplash, the region beneath the cooker hood, the lateral faces of the cabinets and their edges. These components experienced significant thermal attack during the flaming period of the ignition source, primarily due to the heat transfer from the plume flames and hot gases.

To ensure a consistent comparison across tests, variations in initial room temperature were accounted for by calculating the temperature increase ($\Delta T = (T - T_{oo})$ where T_{oo} represents the ambient temperature at each test). This adjustment provided a standardized measure of thermal effects, independent of their initial conditions.

Table 4 summarizes the maximum temperature increases recorded for each experiment. Due to the large number of devices installed in the mock-up, only those with the highest temperatures are showed. To provide a representative assessment of the temperature impact on surfaces, the average temperature for each group of devices located on a specific surface was calculated. For example, the lateral face temperatures were determined as the average of six devices positioned on that surface, while the front face temperatures were calculated using the three devices arranged in a row.

Table 4. Positioning of thermocoples in A-Side (distances in centimetres).

Parameter	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12
Cooker hood	241	238	438	421	548	550	626	629	478	763	678	557
Countertop	43	38	68	63	80	87	93	95	91	114	119	104
Backsplash (wood)	7	6	10	7	9	13	13	13	17	25	24	21
Backsplash[a]	124	123	233	231	333	351	415	410	368	465	477	443
Cabinet A low face[b]	22	20	25	26	30	33	34	35	35	53	55	43
Cabinet B low face[b]	15	14	21	20	24	24	25	26	27	33	31	30
Cabinet A front face[b]	10	6	11	11	19	20	24	21	23	54	47	36
Cabinet B front face[b]	8	7	14	10	16	19	22	19	22	40	26	33
Cabinet A lateral face[c]	95	88	152	143	185	192	211	192	238	293	266	292
Cabinet B lateral face[c]	106	103	173	164	213	208	229	225	241	291	260	294

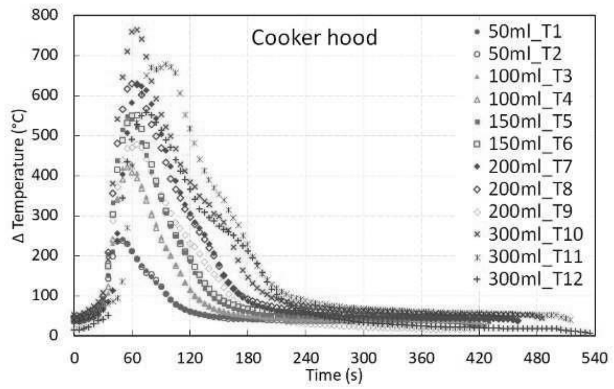
[a]Average of the 3 devices at 60 cm in z-axis. [b]Average of the 3 devices at 48 cm in x-axis. [c]Average of the 6 devices of the face.

The cooker hood exhibited the most significant thermal impact, with temperatures peaking at 763°C at T10, reflecting its direct exposure to flames and hot gases. Similarly, the backsplash experienced extreme heat, with maximum temperatures reaching 477°C at T11.

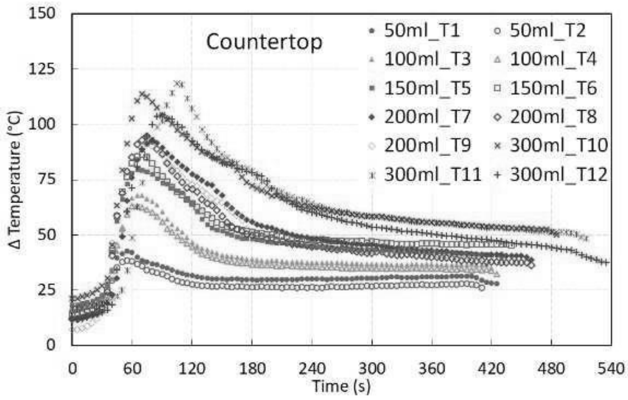
In contrast, the cabinets displayed varying thermal responses depending on their orientation. The lateral faces of both Cabinet A and Cabinet B recorded the highest temperatures, peaking at 293°C and 294°C, respectively, due to their proximity to radiant heat and flame spread. In comparison, the front and low faces of the cabinets registered significantly lower maximum temperatures, with peaks of 54°C and 55°C, indicating reduced exposure to the fire.

Figure 5 displays the temperature increase curves. The heating phase up to ignition is not shown; therefore, t = 0 represents the moment of ignition.

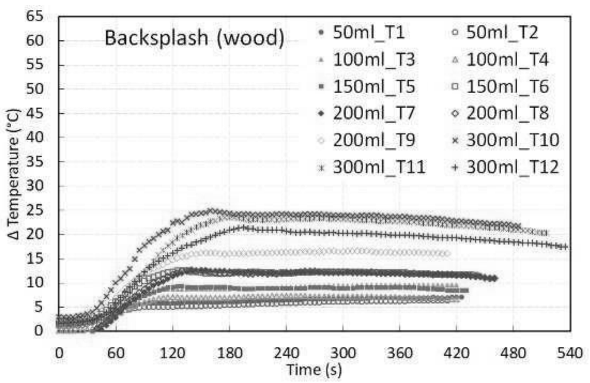
As shown in the curves, once the fire started, the heating rate for all tests and zones was similar. The only notable difference was that the duration of heating was shorter when the initial oil quantity was smaller. Regarding the cabinets, those located on the A-Side, which coincided with the doorway, reached slightly higher temperatures.



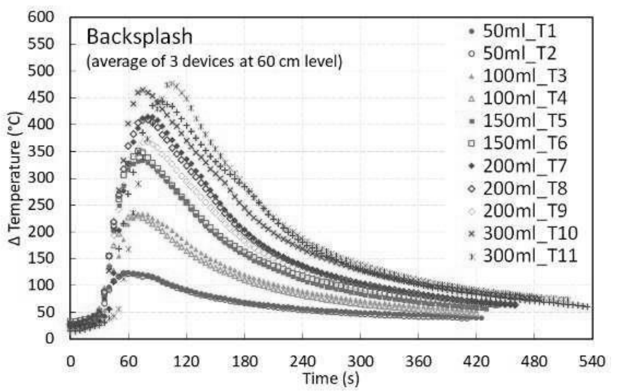
(a)



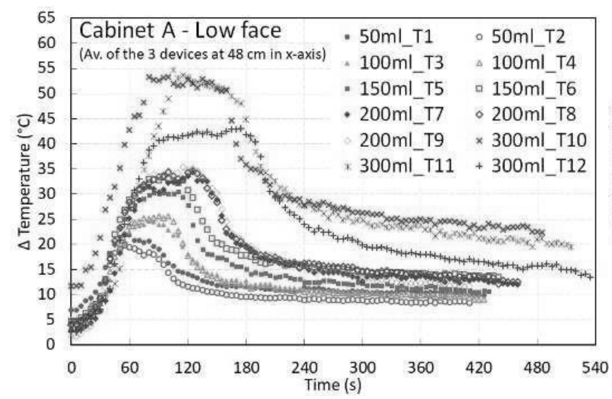
(b)



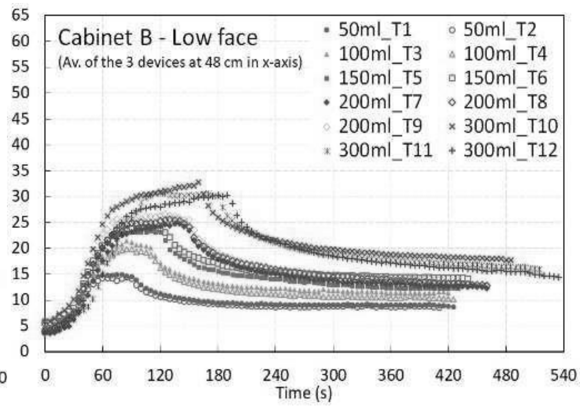
(c)



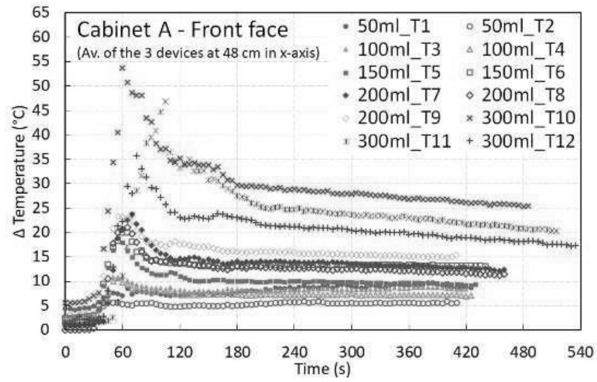
(d)



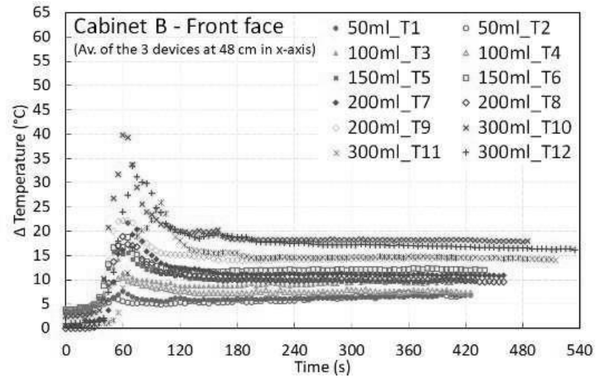
(e)



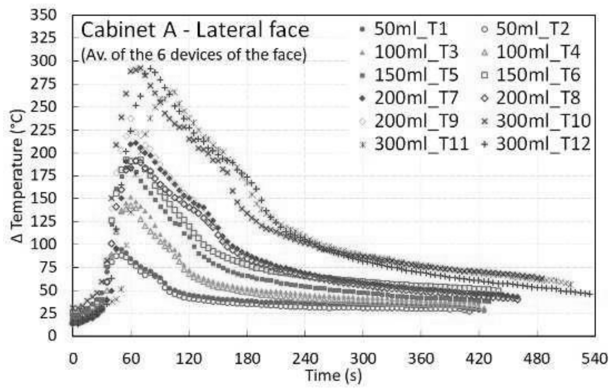
(f)



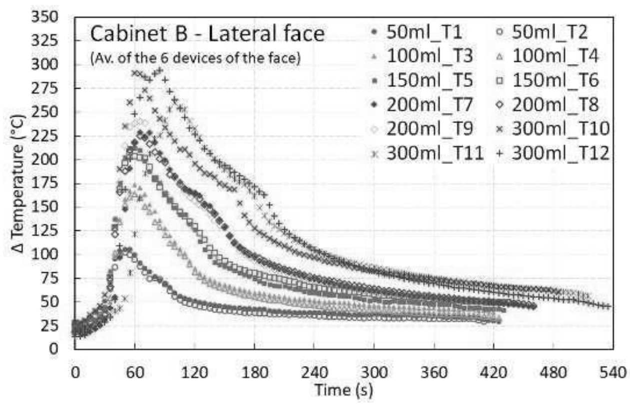
(g)



(h)



(i)



(j)

Fig. 5. Measured temperatures increase: (a) cooker hood; (b) countertop; (c) backsplash wood; (d) backsplash average of 3 devices at 60 cm; (e) cabinet A low face; (f) cabinet B low face; (g) cabinet A front face; (h) cabinet B front face; (i) cabinet A lateral face; (j) cabinet B lateral face.

CONCLUSIONS AND DISCUSSION

The ignition of liquid fuel follows a typical autoignition process of a gaseous fuel-oxidizer-diluent mixture. In kitchen fires, autoignition is more common, as unattended cooking often leads to excessive heating of cooking materials. In such a well ventilated compartment, for autoignition to occur, the fuel concentration must reach at least the upper flammability limit (X_U) and must be surrounded by sufficiently high temperatures [13]. This scenario is particularly critical with small quantities of edible oils.

Ignition times for secondary items can be simplified as a solid heating problem, in which sufficient time is required for the material to reach its ignition temperature. This duration depends on the physical properties of the solid fuel and its orientation. Consequently, the length of the unattended fire becomes a critical parameter, directly influenced by the quantity of liquid fuel available in the cookware fire.

The tests in this study progressively increased the initial fuel quantity, leading to: i) higher energy release, ii) longer autoignition times, iii) and extended flaming periods, and finally iv) more pronounced effects on the elements surrounding the cooktop. The delay in ignition can be attributed to the larger thermal mass and heat absorption capacity of the greater oil quantities, which imply more time to reach autoignition temperatures. As shown in Table 3, the time to ignition differed by up to 375 seconds between tests using 50 ml and 300 ml of oil. A priori, smaller quantities of oil, commonly associated with shallow frying, pose a higher risk due to their shorter time to ignition. Nontheless, these fires did not sustain combustion for extended periods compared to larger quantities. For instance, fires involving 50 ml of oil lasted up to 95 seconds, whereas those with 300 ml persisted for up to 200 seconds. Despite their longer ignition times, larger initial oil quantities caused greater damage to surrounding elements due to the more significant increase in temperatures.

Nonetheless, the fire progression exhibited similar behavior across tests, regardless of the initial oil quantity. Once the flame from the ignition source appears, next key factors should be considered:

i) Flame Impingement: Flames from the cookware made direct contact for a few seconds with the closest obstacles, particularly the lateral panels of the cabinets and the upper zone of the backsplash. This effect was notably more pronounced in tests involving larger initial quantities of oil (e.g., 150 ml, 200 ml, and 300 ml). This interplay between the buoyant plume, ceiling jet, and fuel-rich combustion dynamics played a crucial role in the progression and behavior of the fire during the tests.

ii) Convection Heat Transfer: Hot gases from the ignition source spilled over and accumulated beneath the cooking hood until they overflowed. This process created a hot layer below the hood, leading to increased temperatures on the lateral panels of adjacent cabinets through convection.

iii) Radiation heat transport: Radiation heat transfer, governed by the Stefan-Boltzmann law where temperature is raised to the fourth power, plays a significant role in heating surfaces near the flame for larger fires. Surfaces directly exposed to the flame's radiant energy, such as the lateral panels of upper cabinets and the backsplash closest to the cooktop, experienced the most substantial temperature increases. A simple calculation illustrates this effect: for a lateral surface 38 cm wide and a cylindrical flame with a 10 cm radius at a center-to-center distance of 32 cm, the resulting view factor is 0,17. By contrast, the lower surfaces of the cabinets were not directly impacted by the flame's radiation, leading to only a slight temperature increase. A calculation of the view factor between two perpendicular surfaces separated by 23 cm produces a value of 0,054.

Tests with larger oil quantities displayed early signs of damage on cabinets, suggesting a potential vulnerability. This may well increase if larger initial oil quantities were employed, such as commonly seen in deep-frying techniques.

The results of this study highlight the critical importance of considering fire dynamics and heat transfer in kitchen layouts to enhance fire safety. The sequence of events, energy release, and temperature measurements demonstrate how the initial fuel quantity significantly influences fire intensity, duration, and thermal effects on surrounding areas. These findings emphasize the need for thoughtful design and material selection to mitigate the risk of secondary ignitions.

Specifically, the positioning of kitchen elements, such as upper cabinets and cooker hoods, might play a pivotal role in determining the extent of heat exposure and potential damage. Increasing the distance between cabinets or incorporating gaps between the cooker hood and adjacent surfaces can reduce temperatures and decrease the likelihood of ignition. Additionally, the choice of materials is equally critical for safety. Metallic backsplashes, for instance, effectively prevent ignition and limit the spread of fire, while the lateral faces of cabinets can provide an added layer of protection.

ACKNOWLEDGMENTS

We would like to express our sincere gratitude to the following organizations for their support: DEFIANCE Grant PID2023-150202OB-I00 funded by MICIU/AEI/ 10.13039/501100011033 and by ERDF/EU; Consejo de Seguridad Nuclear for their cooperation and co-financing of the project Análisis de modelos numéricos y experimentales para la investigación de incendios en centrales nucleares (FIRENUC) and Consejo de Seguridad Nuclear for their support of the research project SUBV-18/2022 (NUCLEVS – Validación, calibración y aplicación de modelos de propagación de incendios en escenarios reales de Centrales Nucleares). Their contributions have been invaluable to the success of this research.

REFERENCES

[1] M. Ahrens, R. Maheshwari.Home structure fires. NFPA - National Fire Protection Association. Fire Analysis and Research. Quincy, MA, 2021.

[2] M. Ahrens. Home Cooking Fires. NFPA - National Fire Protection Association. Fire Analysis and Research. Quincy, MA, 2020.

[3] W. Tseng, S.W. Chien, T.S. Shen. Comparative Analysis of Taiwan Fire Risk with Asia/Oceania and Other Countries around the World, Fire Saf. Sci. 9 (2008) 981-990.

[4] F.T. Orthoefer, G.R. List. Dynamics of frying. Deep frying (second edition), AOCS Press, pp 253-275, 2007.

[5] B. Andres, M.S. Hoehler, M.F. Bundy. Fire resistance of cold-formed steel framed shear walls under various fire scenarios. Fire maters. 44(3),(2020) 352-364.

[6] W.K. Chow. Heat release rate of an open kitchen fire of small residential units in tall buildings. In International High Performance Buildings Conference, paper 100, 2014.

[7] A. Hamins, S.C. Kim, D. Madrzykowski. Characterization of stovetop cooking oil fires. J. Fire Sci., 36(3), (2018) 224-239.

[8] Refinement of Temperature-Limiting Control Systems for Preventing Oil Ignition on Gas and Electric Cooktops. Primaira LLC, 2015.

[9] J.B. Dinaburg, D.T. Gottuk. Development of standardized cooking fires for evaluation of prevention technologies: data analysis. NIST GCR 15-917-36, NIST - National Institute of Standards and Technology, 2014.

[10] T. Jhatial. Thermal characterization of electric stoves. Master's Thesis. Aalto University, Finland, 2021.

[11] ISO 9705-1:2016. Reaction to fire tests — Room corner test for wall and ceiling lining products — Part 1:
Test method for a small room configuration. ISO - International Organization for Standardization. 2016

[12] M. L. Janssens, M. L. Measuring rate of heat release by oxygen consumption. Fire Technol, 27 (1991) 234- 249.

[13] J.Q. Quintiere. Fundamentals of fire phenomena. John Wiley & Sons, Ltd. 2006.