fire

Article

FDS Results for Selecting the Right Scenario in the Case of a Building Fire: A Case Study

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Abstract: On the evening of 5 April 2014, at a building located on 122 Tomis Boulevard, Constanta Municipality, Constanta County, Romania, a restaurant with its kitchen on the ground floor and a lounge bar located on the first floor experienced a fire, one that resulted in four victims and total building destruction. An important step in the technical-scientific expertise was the investigation of the incident based on the elaboration of two fire scenarios using the Fire Dynamic Simulator (FDS) model, which observed the fire propagation, the generation of toxic gases (carbon monoxide that disoriented and intoxicated the victims, three of whom could not save themselves) depending on the location of the plausible ignition sources, and explained the destructive effects. This paper focuses on the steps required to identify the critical conditions that led to the occurrence of the unwanted event. Based on the calculations, hypothesis, and FDS simulations, the mechanism of the event occurrence was considered to be strongly related to the onsite observations and criminal file issued by the state authorities.

Keywords: fire forensics; FDS; fire modeling; large building fire; case study

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1. Introduction

The origin of fire represents one of the most important hypotheses that a forensics fire investigator develops and verifies during an investigation. Along with determining the cause of a fire (i.e., determining the first material ignited, the source of ignition, and the circumstances that caused the event), these activities are based on scientific methods.

Investigations of fire and explosion incidents frequently have goals that go well beyond simply figuring out what caused the occurrence to happen. Any fire investigation seeks to identify the elements of a specific type of incident that led to a fatality, a serious injury, property damage, or other undesirable outcomes [1]. Due to the multiple variables that go into defining a fire and governing its development and spread, no two fire scenarios are alike. However, the scientific approach allows the highlighting of some general laws and principles that ensure the reproducibility of the phenomena. Based on an understanding of the principles of combustion, the burning characteristics of fuels, the laws of heat transfer, and the way fire propagates in an enclosure, the investigator can evaluate a specific fire and determine the cause of the fire.

When, during the process of formulating conclusions, an acceptable correlation is not reached between the results of the analysis carried out and the clear evidence presented by the investigator, the existing data are reanalyzed, and new data are obtained through physical experiments in laboratories, computer simulations, and numerical modeling of the event.

The primary goal of these simulations is to introduce and apply mathematical and physical concepts to explain the fire behavior of materials and the dynamics of fire. By developing a virtual model of the geometry of the area affected by the incident and running computer simulations for various fire scenarios, it is possible to gain a better understanding of combustion processes and fire dynamics [2,3]. This information is crucial for determining how a fire will develop over time, how exposed its occupants will be, how likely they are to survive, and how to analyze combustible materials and post-event indicators [4–6].

To emphasize the significance of employing numerical modeling in the scientific analysis of fire-type events, this paper presents a case study based on an actual fire that happened in the evening of 5 April 2014 at a building located in the urban area, a restaurant with a kitchen in the ground floor and a lounge bar on the first floor [7].

The building was built on a wooden structure, beams, and supporting pillars made of fir wood, framed by the brick walls of the neighboring buildings. The kitchen was located on the basement level, without windows, provided with a brick chimney for the gas-powered bread oven, which intercepts a wooden beam, which is a supporting element of the floor. Moreover, the upper part of the chimney penetrates the roof of the first floor, but ends with a flexible aluminum pipe, without self-support. The floor is made with OSB boards, double-glazed windows, and external upper-floor wall insulated with unplastered extruded polystyrene boards (EPS).

This paper explains the phenomena of fire propagation, its dynamics, and the concentrations of emitted gases in two situations of fire initiation: the ignition of the wooden beam spanning the brick chimney through which the hot gases and incandescent particles from the flour used in the process of bread making are discharged, due to an unobstructed hole in the brick chimney. Further, the same hot gases and incandescent particles from the flour were used to cover the bread tray as a source of ignition, but when positioned outside the building, came into contact with the polystyrene that was used to cover the walls, because of the non-conformity of the flexible, non-self-supporting aluminum tube and extension of the brick chimney. The key elements for the elucidation of this case are the position of the source of ignition and the position of the four victims who were surprised by the start of the fire. The four girls were, at that moment, in a locker room without windows, preparing for their dance show, which was set to take place on the ground floor. One of the victims was rescued by the owner of the restaurant, who hardly managed to resist the flames and hot gases in the doorway area and pull her out of the locker room before dragging her down the stairs. This was the only real rescue intervention, as the firefighters were stopped by the flames and the unstable wooden structure from going upstairs, their actions limited to intervening via a fire extinguishing agent, which prevented the spread of the fire to neighboring buildings. The other three victims, disoriented due to smoke and lack of visibility, were unable to rescue themselves and were later found burned.

2. Materials and Methods

A series of computer modeling of the fire were carried out to explain and interpret the mechanism of the fire produced on the premises of the mentioned restaurant, in the city of Constanța, using the Thunderheadeng PyroSim software package composed of an interactive graphic interface for the simulation of fire dynamics (Fire Dynamics Simulator—FDS), as well as the Smokeview application, which enabled the graphical, three-dimensional visualization of the results.

FDS is a computational fluid dynamics (CFD) model that focuses on the virtualization of fluid flow in in-flow affected environments, using Navier–Strokes equations appropriate for low velocities and heat flows with emphasis on heat and smoke transport as the computational background. The partial derivatives of the mass, momentum, and energy conservation equations are approximated as finite differences, and the solution is continuously updated on a three-dimensional mesh. The thermal radiation is calculated by the finite volume technique on the same computational mesh as for fluid flow. Lagrangian particles are used to simulate smoke movement, as is water spraying through sprinklers or fuel injection [8].

In the literature, many researchers have done numerical and experimental studies on the issue of fire dynamics. FDS was used for various studies of fire dynamics and people evacuation from large shopping centers [9–11] or university campuses [4]. Other researchers conducted studies in road tunnels to statistically and experimentally evaluate the effectiveness of the current emergency ventilation system, smoke dispersion [12], or occupants' egress when controlling fire-smoke spread [13,14]. Rapid fire spread on flammable vertical cladding, in the case of high-rise buildings, was also a field of research using computer simulations [15,16]. There are many other studies regarding the technical and forensics investigation of large-burn scale disasters, e.g., nightclub fires [17–19], or natural wildfires [20]. All of these various studies indicate the wide applicability of the FDS numerical model in the fire safety field.

2.1. Input Data

Information regarding the computational domain defining the geometry, the environmental conditions, the real solid geometry, material properties, combustion kinetics, and the intended output data are among the data that must be entered. The numerical grid consists of several cells, usually uniform, to which all geometrical characteristics of the bodies in the scenario must conform. A body smaller than the dimensions of a mesh cell will be approximated to its volume or not considered. Specific characteristics are attributed to the surfaces of solids, and materials are defined by their thermal conductivity, density, specific heat, thickness, burning behavior, etc.

Any simulation of a fire scenario invokes specific properties for walls, floors, ceilings, and furniture. FDS treats these objects as multi-layered solids, so many of the real objects can be "seen" as an approximation of the real properties. Describing these materials in an input file, as well as describing their behavior during burning at different heat fluxes, are the hardest tests for the user, and the properties are even harder to obtain.

2.2. Output Data

FDS calculates the temperature, density, pressure, velocity, and chemical composition of each cell of the mesh for any small period. Typically, the simulation assumes many grid cells from hundreds of thousands to millions or tens of millions, in cases of large-scale geometries. In addition, FDS calculates the solid surface temperature, heat flux, amount of mass loss, and various other quantities. The large amount of information involved in the calculation results in output files of considerable sizes, even for a small fraction.

2.3. Uncertainty of FDS Numerical Modeling

The complexity of fire phenomena indicates that the results of any model's computations will be subject to a substantial degree of uncertainty, regardless of how it is implemented. FDS can provide valuable insight into how a fire may have ignited and developed. It must be mentioned that the model is only a simulation. The results generated by numerical simulation are dependent on a variety of input data: combustible material properties, duration, geometry, and ventilation contribution. In reality, the exact knowledge of every detail in a case of a fire event (fire site details, fuel load, or fire timeline) is hardly ever known, so estimations will be used during model design. A first estimation is the energy release rate of the initial fire source, as a starting point of the fire development and spread throughout the structure for creating the fire scenario. Material properties can also induce uncertainties, due to the lack of complete information about the nature and thermo-physical properties of the materials and objects on site. In this case, common values for these properties are used and collected from the literature or online available databases. FDS's capability to accurately predict the temperature and velocity of the fire gases is a major factor related to uncertainty. This factor can be evaluated by previously conducted experiments (lab-scale or full-scale), measuring, and comparing quantities of interest [21]. According to NIST and the model developers, FDS is extensively validated. It is stated that, in the case of relatively simple fire-driven flows, the results are within the experimental uncertainty of the values measured in the experiments. In large-scale fire tests, FDS results were found to be within 15% of the measured temperatures, while the heat release rate was within 20% of the measured values [22,23]. It is often recommended that simulation results be presented as ranges to include the predictable uncertainty-generating part.

2.4. The Objective of Virtual Simulation

To evaluate the two hypotheses that could have led to the fire in the mentioned restaurant and to identify the hypothesis with the highest probability of occurrence, it is essential to study the phenomenon of combustion, which includes estimating the temperatures of the hot gases and their distribution in space and time. This estimation can be used to explain the different stages of the fire, as well as how it spread from the level of the premises to the entire building and the neighboring building.

The virtual fire simulations are primarily intended to estimate the temperatures in the vicinity of the ignition source, the possibility of combustible materials being ignited from the presumed source, and the propagation of the flame front to neighboring rooms, where various materials with important support in the development of the fire were present. The further propagation of the flame front, the amount of heat released, and the movement of hot gases in the premises of the restaurant located in Constanta can be approximated based on the resulting temperatures.

2.5. Characterization of Combustible Materials inside the Studied Restaurant, Constanta Municipality

According to the findings on the site and the technical scientific report of the probable cause of the fire (produced by ISU Dobrogea, Constanța county, Romania), the structure of the building where the restaurant was located at the time of the occurrence might be defined as follows:

- Building structure facing Tomis Boulevard: masonry pillars, exterior masonry walls, and wooden staircase to the first floor.
- Building structure facing I. Bănescu Street: wooden pillars and beams, the floor between the ground floor and the first floor supported by wooden beams, clad on the upper part with wooden boards, a PVC foil layer, then laminated flooring, and clad on the lower part with sheet metal, tarred cardboard, and mineral wool. The external walls were composed of masonry and were positioned near the property line.
- The roof was made of sheet metal on wooden roofing.
- The first-floor walls and ceiling were finished in PVC paneling.

Combustible materials identified at the fire scene (wood of various types, PVC paneling, cotton textiles, polyamide, polyester—interior decorations with Arabic and Lebanese influences), present in large quantities, explained both the extremely rapid spread of the fire and the release of a significant amount of smoke and toxic gases. The physical and thermal characteristics of the materials with a major contribution to the fire found on-site and used in the computer simulation, taken from the PyroSim application database and different sources available online, are given in Table 1.

Table 1. Physical and thermal properties of main materials involved in fire.

Material	Density (kg/m^3)	Specific Heat (kJ/(kg·K))	Thermal Conductivity (W/(m·K))	Heat of Combust (kJ/kg)	Heat Release Rate per Area (kW/m^2)	Ignition Temp. (°C)
Wood [24,25]	640	2.85	0.14	17,000	200	200
PVC [26]	1380	1.29 (23 °C) 1.35 (50 °C) 1.47 (100 °C) 1.59 (200 °C)	0.192 (23 °C) 0.175 (50 °C) 0.147 (100 °C)	20,000	312	390
XPS [27]	28.9	1.5	0.03	3910	200	360
Textile [28]	240	1.357	0.1	17,000	250	220

2.6. Virtual Simulation of the Fire inside the Building of the Restaurant, Constanta Municipality

The geometry of the entire structure was modeled in FDS to perform the computer simulation of the two scenarios that could have started the fire in the restaurant (Figures 1 and 2).

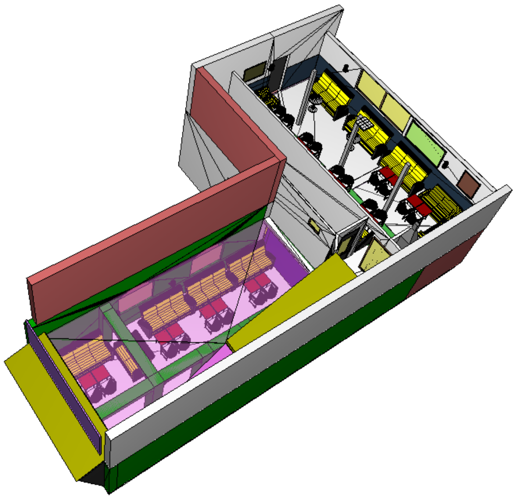
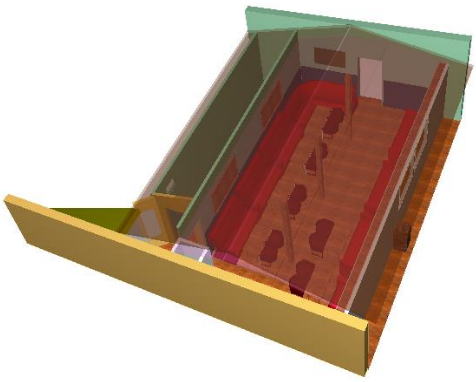
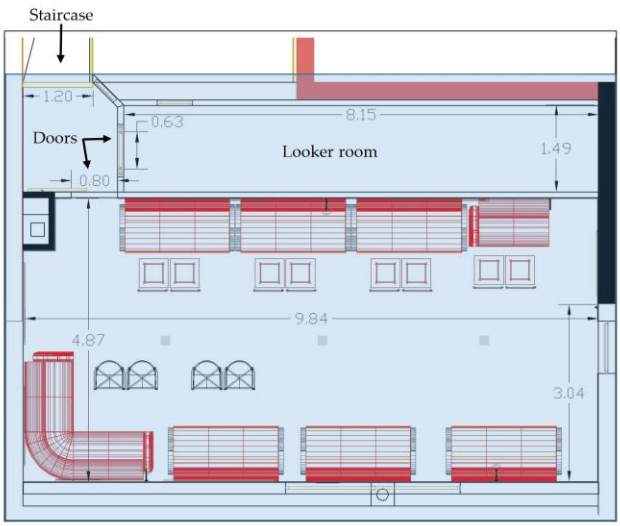


Figure 1. General plan: Ground floor and first floor.



(**a**)



(**b**)

Figure 2. Virtual geometry for the first floor (**a**)—model detail; schematic graph of the first floor (**b**).

This geometry was further segmented to run numerous tests, by stages of development of the phenomena, due to the vast computational volume required by the scale of the building, the complexity of the materials, and its interior components.

Two distinct stages were followed in the process of carrying out the computer simulation. The first stage included the analysis of potential ignition sources and the emergence of the initial flame front. The second stage involved demonstrating how the fire spread in the customer lounge, located on the first floor of the restaurant, in the context of each of the hypotheses pursued, with its incredibly quick evolution, favored by the flammable nature and the large quantities of building materials and decorations found in this room. At the same time, these materials also explained the presence of the dense smoke noted by the victims and witnesses, as evidenced by their statements, as well as the lethal concentration of carbon monoxide and other toxic hot gases produced by the combustion of the PVC paneling, i.e., the materials used to make the sofas, the decorations, etc.

2.7. *Description of the Event*

The fire was reported to the National Emergency Call Service by telephone at 22:38; the fire crews arrived at 22:44. By the time the firefighters arrived, the restaurant owner attempted to intervene and rescue the girls in the upstairs locker room, managing to open the locker room door and evacuate the first girl, who was lying on the floor near the entrance. Regarding the rescue of the victim, there is no data on the exact time of the extraction. What is certain is that for the other victims, due to the high temperatures developed by the fire which made rescue intervention impossible, the radiative heat field and flames kept them away from access to the floor. Ultimately, the fire led to the collapse of the floor structure between the building's levels.

The computer simulation presented in this study does not aim to simulate the entire event, but only the time interval necessary to reach the carbon monoxide concentration that can lead to the loss of orientation, in the case of victims caught in the fire, proven by the state of unconsciousness in which the saved victim was found during the rescuers' intervention near the locker room door.

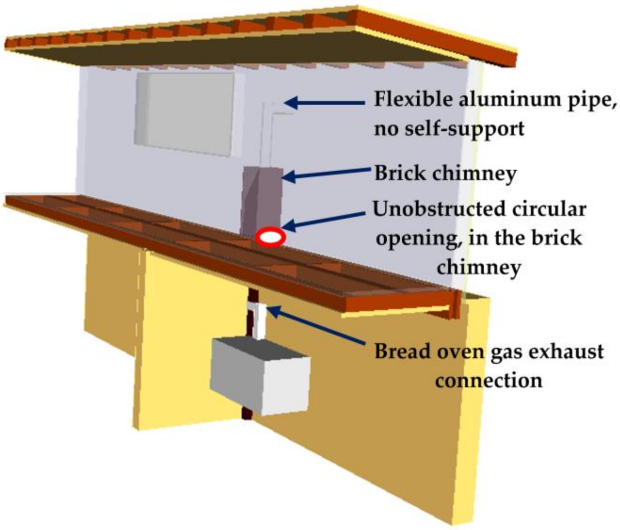
According to the literature [29,30], the effect of carbon monoxide on humans is manifested by headache, weakness, disorientation, nausea or vomiting, confusion, blurred vision, loss of consciousness, and death, depending mainly on the concentration of carbon monoxide and the time of exposure. Other factors such as age, weight, and previous health can also influence the consequences of exposing the human body to a high CO concentration. For the present work, taking into account the concrete circumstances of the event (time of observation of the fire and call to National Emergency Call Service, the arrival time of the fire brigade—6 min), and taking into account the estimates of the time needed for the development of the initial outbreak (until observation) and the deployment of the fire brigade until the firefighters went up the stairs to the locker room floor, a disorientation dose with CO of 400 ppm for 10 min of exposure of the girls in the locker room was considered as a reference.

The relevance of the 30 s of computer simulation is justified by the testimony of the surviving witness, who reported that the locker room had no windows to the upstairs premises (bar), that at some point they smelled smoke, the lights turned off (as the floor power supply cable, being in the vicinity of the floor support beam intersecting the brick chimney, was the first item affected by the initial outbreak), and the smoke made them very disoriented, they could not find the door. Concerning the death of the three victims, the forensic certificate shows carbon monoxide poisoning as the cause of death, and the thermal effects on the bodies occurring afterward, which is very useful in the elaboration of scenarios and interpretation of the results by the authors of the paper.

a. Ignition Source

According to the on-site findings, the fire footprint indicates heavy burning of the wood beams and walls in the area above the kitchen from the chimneys to the locker room. The scenarios of fire occurrence and development simulated with the Pyrosim software package are based on the two hypotheses describing the mechanism of the event, which highlight the potential initial fire sources:

- Fir wood beam supporting the floor separating the ground floor from the first floor, in front of the unobstructed hole/opening identified on-site in the brick chimney, at an elevation above the bread oven connection (Figure 3).
- The extruded polystyrene boards covering the eastern wall of the restaurant floor, near the brick chimney (polystyrene is also incorporated in the plaster/mortar material of the chimney (Figure 4).



(**a**)

(**b**)

(**c**)

Figure 3. Hypothesis (1). Building section (ground and first floor), eastern wall (**a**); details of the unobstructed hole in the brick chimney (**b**); upper limit of the chimney with flexible aluminum tube extension (**c**).

The geometry of the first building's floor is presented in Figure 5.

To capture the fire ignition details and the initial propagation of the flames, a sectional geometry was used for the half part including the two types of ignition sources (internal and external), and, for the final, a complete geometry of the floor was used, including the locker room, where the four victims were located. The location for the virtual measuring devices (temperatures and CO concentration) is also presented in the figure.

The first model is the virtual representation of the entire first floor of the restaurant building. For the computation domain discretization, a mesh of 11.50 m $\times$ 10.00 m $\times$ 4.24 m was used. The grid cell size (mesh resolution) was 0.1505 m $\times$ 0.1010 m $\times$ 0.1010 m, totaling 461,538 cells.

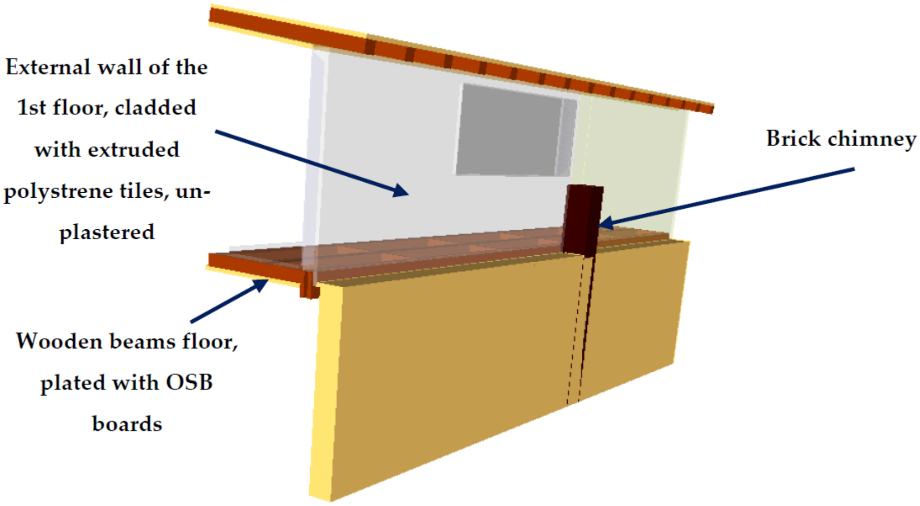


Figure 4. Building section (ground floor and first floor), eastern wall. Hypothesis (2).

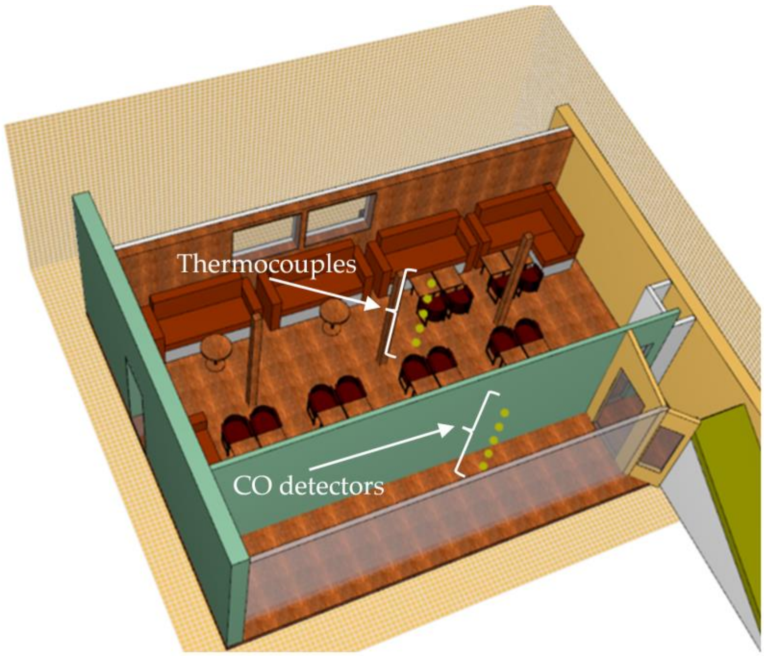


Figure 5. The virtual model of the geometry used for fire simulation (the 1st floor of the restaurant).

For the simplified geometry, the room area includes both of the hypothetic ignition sources (internal and external), and the computational domain consists of a mesh of 10.50 m × 4.90 m × 4.00 m with a uniform distribution. The mesh resolution, in this case, is 0.10 m × 0.10 m × 0.10 m, and the total number of cells is 205,800.

When choosing the resolution of the computational domain, it was taken into account that, since we are talking about relatively complex geometries, each element within the model (e.g., obstructions, vents) must be correctly related to the mesh, to avoid repositioning or ignoring it during the simulation. To achieve optimal simulation accuracy, it is important to use mesh cells that are approximately the same size in all three directions [8]. At the same time, all combustible materials documented in the statements and identified on-site, included in the computer modeling, must be able to participate in the evolution of the simulated fire, through all three heat transfer modes (radiative, conductive, and convective), as confirmed by the material consumption.

Following the on-site investigation, and the witness statements and existing documents, no ventilation systems were found in the restaurant space on the ground floor or in the bar and locker on the building's first floor, so they were not considered in the computer simulation of the fire.

3. Results

3.1. Hypothesis (1)

The first hypothesis assumes that the fire ignited from the wooden beam supporting the floor between the two buildings levels, near the hole or unobstructed opening observed at the fire scene in the brick chimney. Due to this opening, placed at a higher level than the bread oven connection, some flue gases and incandescent flour dust particles could have come into contact with the resinous material of the floor support beam, which is easily combustible. The following figures present the fire development stages for this scenario (Figures 6–10).

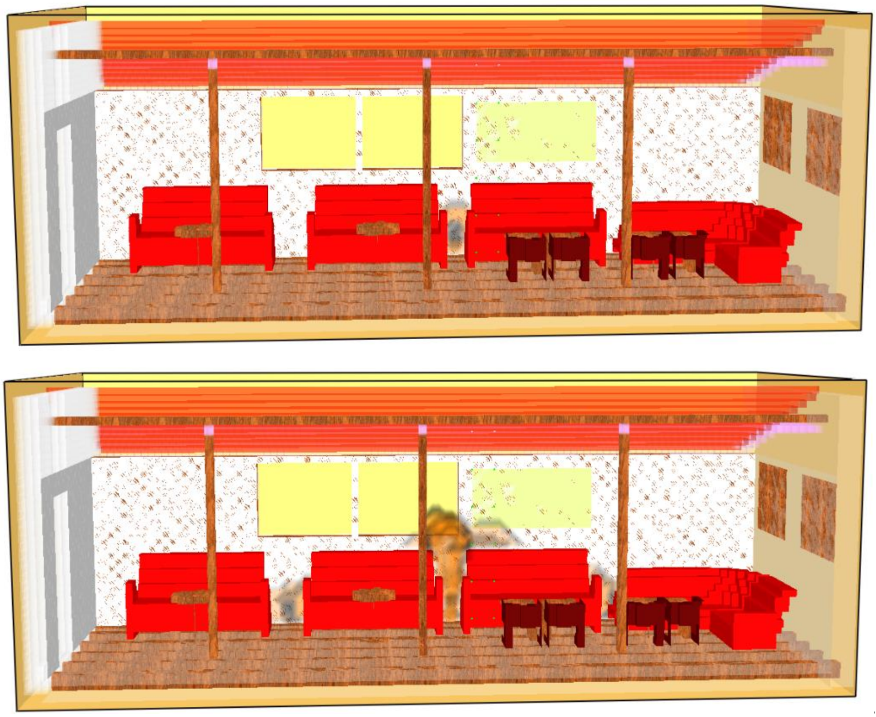


Figure 6. The fire ignites the floor's wooden support beam and spreads into the first level of the restaurant lounge.

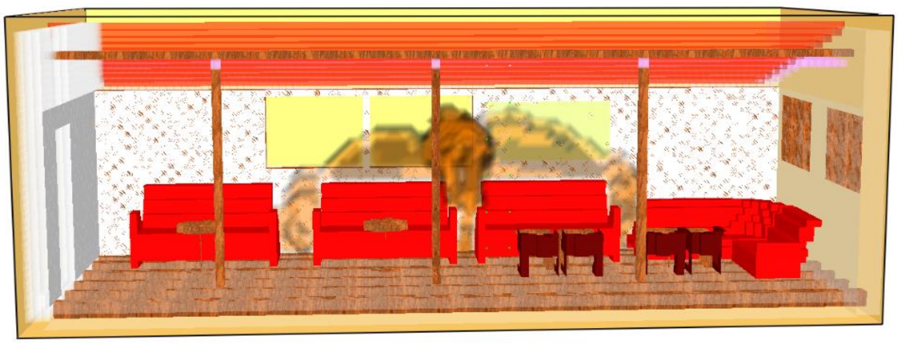


Figure 7. Fire developing on the inside of the eastern wall.

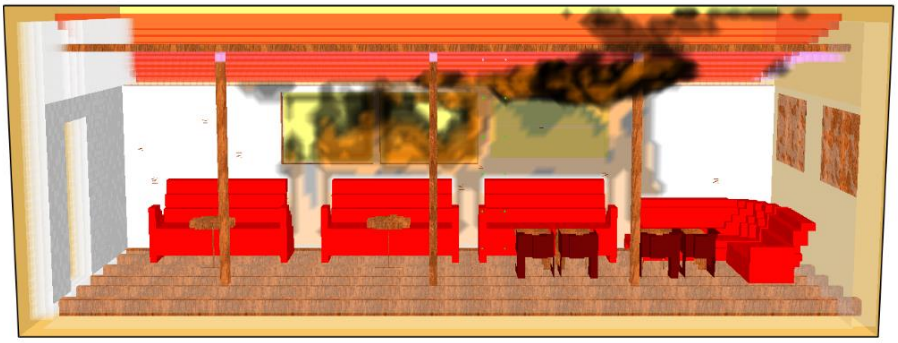


Figure 8. Fire spreading to the ceiling.

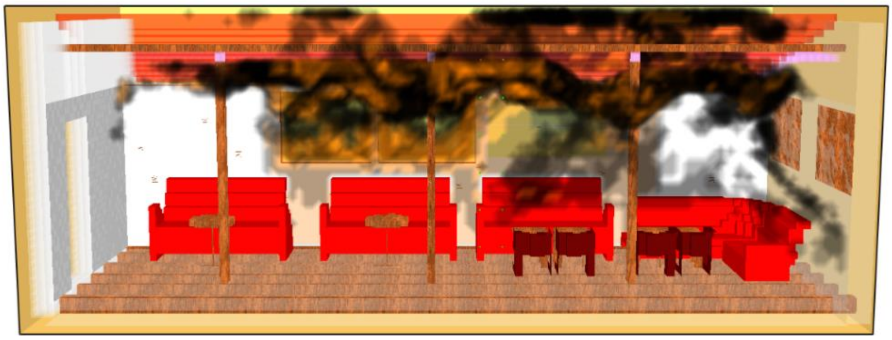


Figure 9. Combustion of furniture by thermal radiation and hot gases.

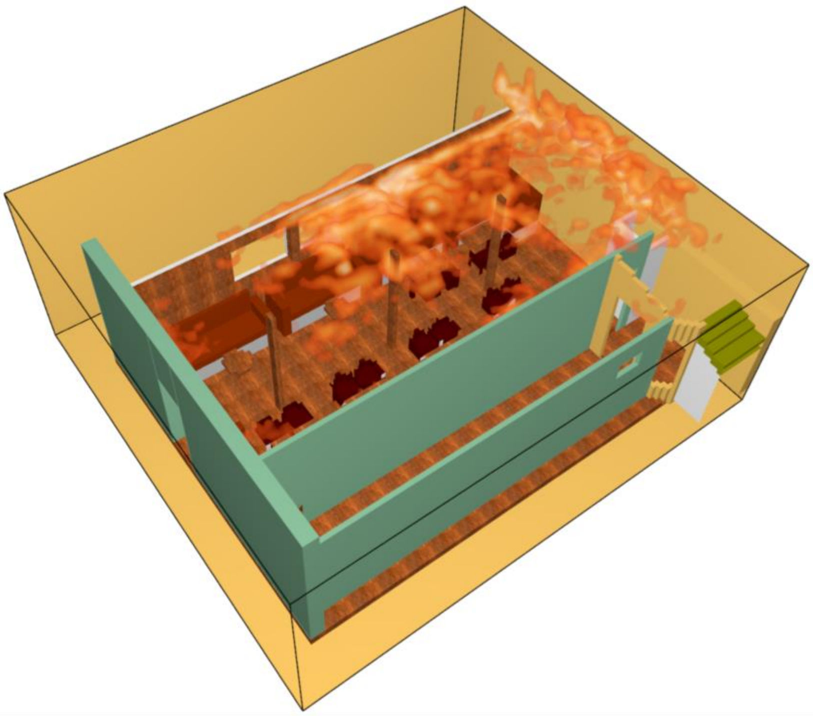


Figure 10. Generalization of the fire at the entire level of the 1st floor.

To estimate the temperatures inside the restaurant hall, a series of virtual thermocouple-type devices were used, distributed at equal distances of half a meter, vertically, on the longitudinal axis of the room, on the plane perpendicular to the eastern wall, next to the brick chimney (Figure 5). The time evolution of these temperatures in the first 30 s of the simulation, in the case of hypothesis (1), is presented graphically in Figure 11.

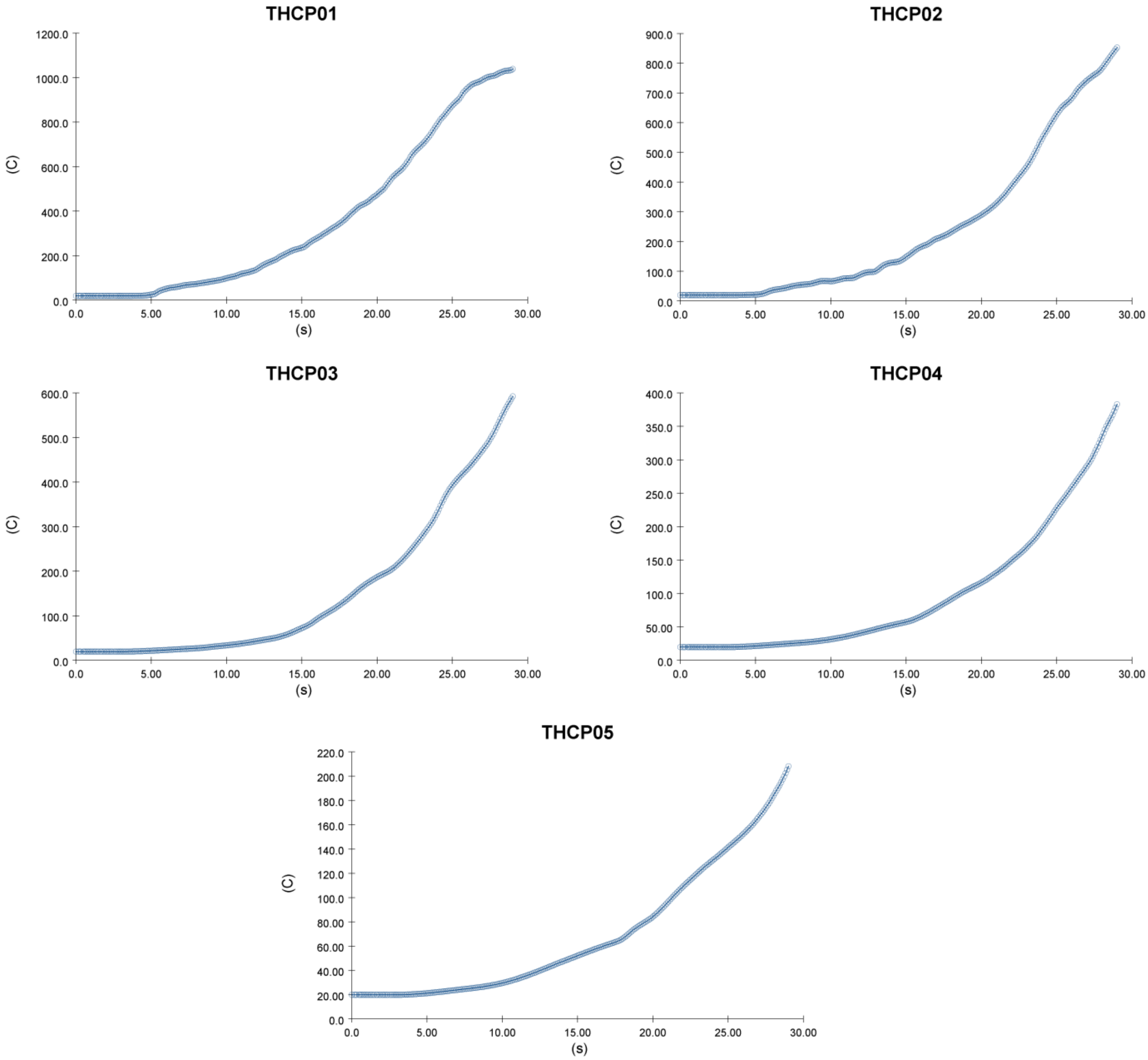


Figure 11. Room temperature evolution in time in the first 30 s of fire simulation (Hypothesis 1).

Similarly, several virtual volume fraction measuring gas-phase devices were employed to track the evolution of the carbon monoxide concentration inside the room atmosphere during the fire. The monoxide concentrations read by the virtual sensors are shown in the diagrams below Figure 12.

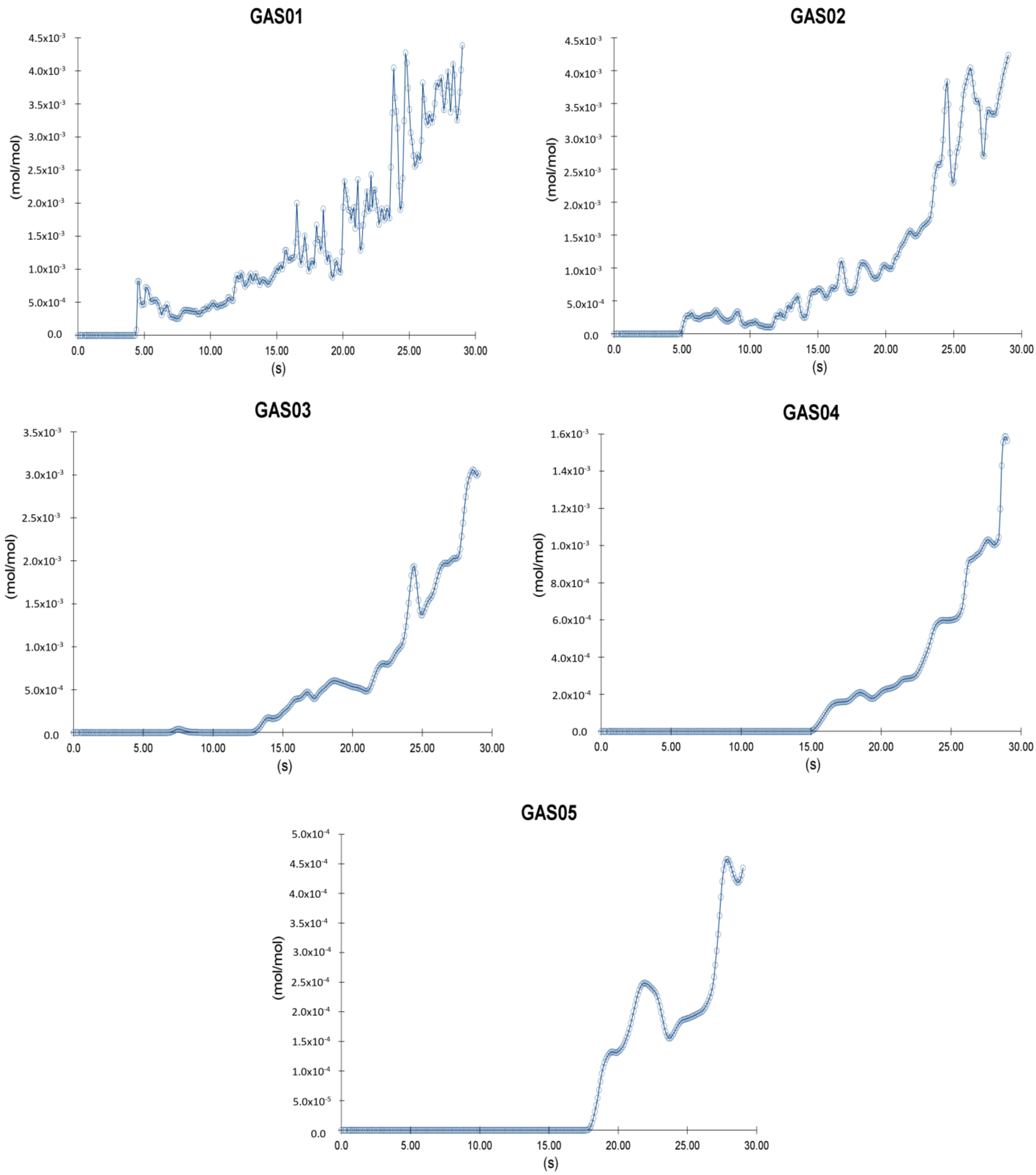


Figure 12. CO volume fraction diagrams.

3.2. Hypothesis (2)

The second hypothesis presumed that the fire was ignited and developed from the outer eastern wall, clad with extruded polystyrene boards and un-plastered. The incandescent flour particles used to cover the bread tray, discharged through the flexible aluminum tube without self-support, extension of the brick chimney, not surpassing the height of the roof, could have come into contact with the polystyrene insulation of the outer wall of the restaurant floor, leading to its fire (Figures 13–16).

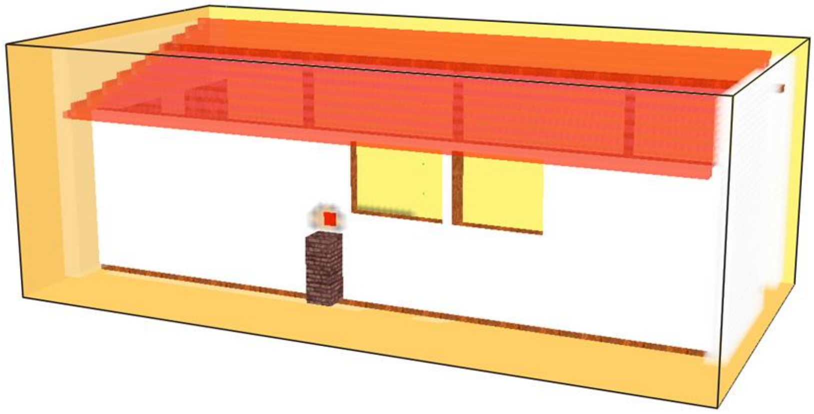


Figure 13. Ignition of the eastern wall cladding with extruded polystyrene due to the incandescent flour particles emitted through the flexible aluminum tube without self-support or extension of the brick chimney.

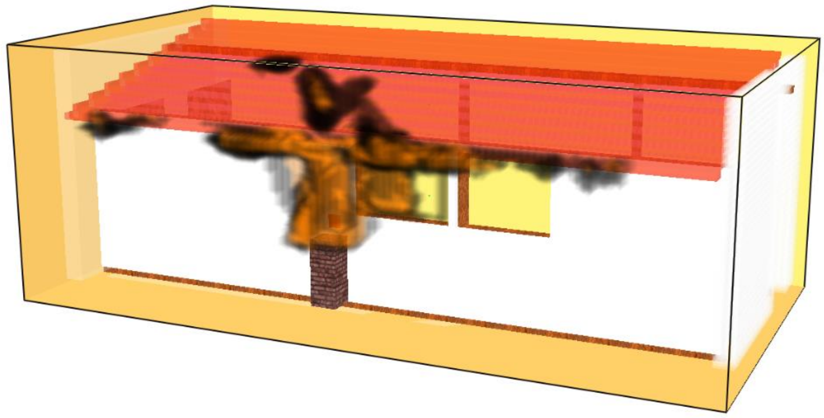


Figure 14. The spread of the fire on the outside of the eastern wall of the floor, favored by the combustible properties of the polystyrene insulation.

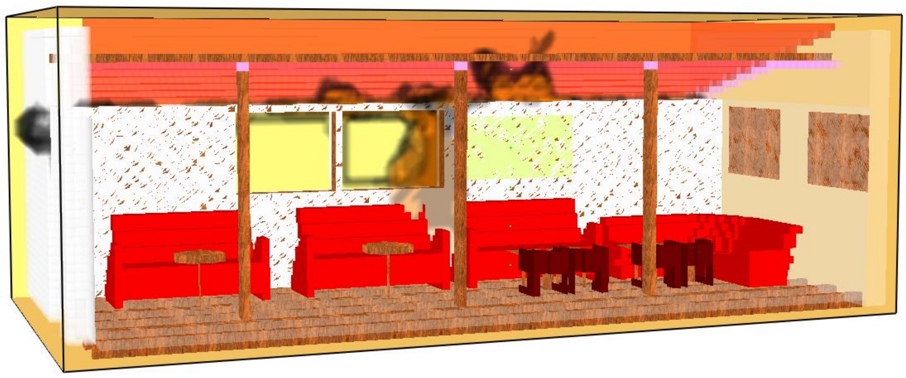


Figure 15. The spread of the fire inside the restaurant floor, through the window, and the ignition of the furniture in the room (sofas located nearby windows).

Figure 17 presents the temperature readings of the virtual thermocouples, placed inside the restaurant, while Figure 18 presents the volume fraction of carbon monoxide.

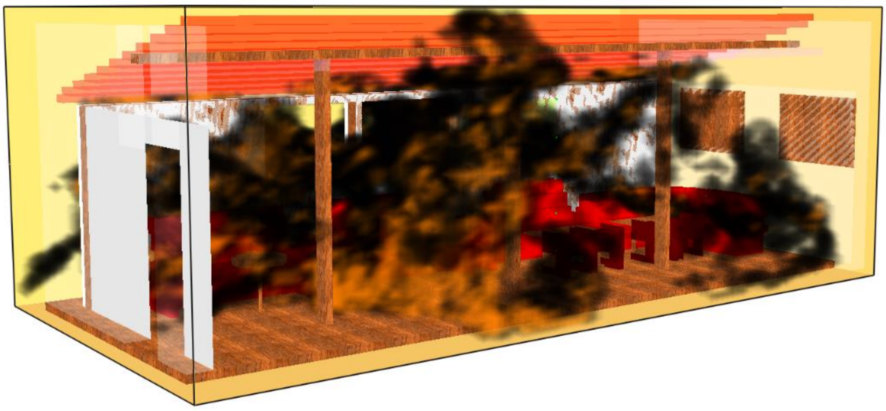


Figure 16. Generalized fire spreading throughout the restaurant floor.

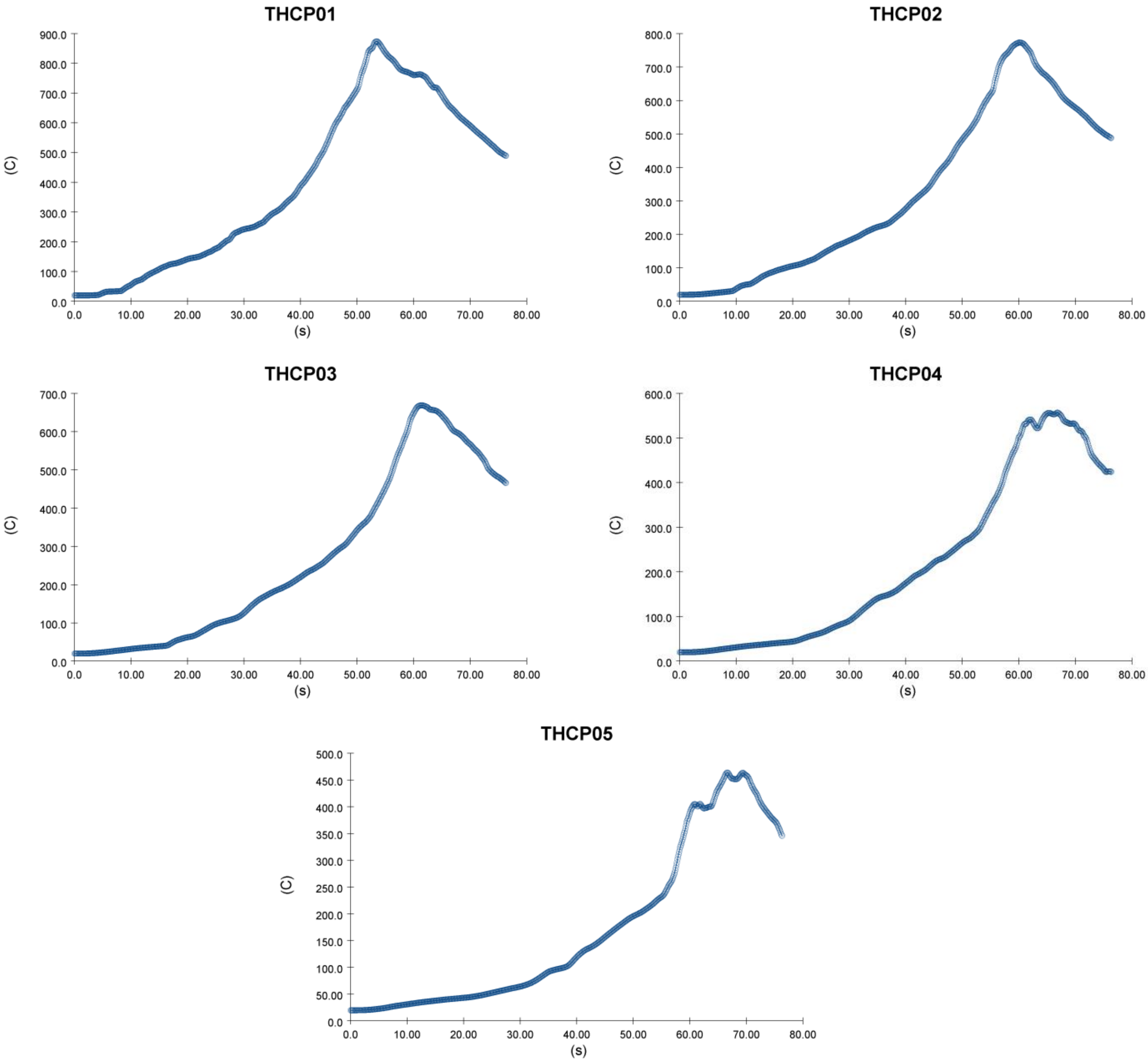


Figure 17. Room temperature evolution in time, in the first seconds of the fire simulation (Hypothesis 2).

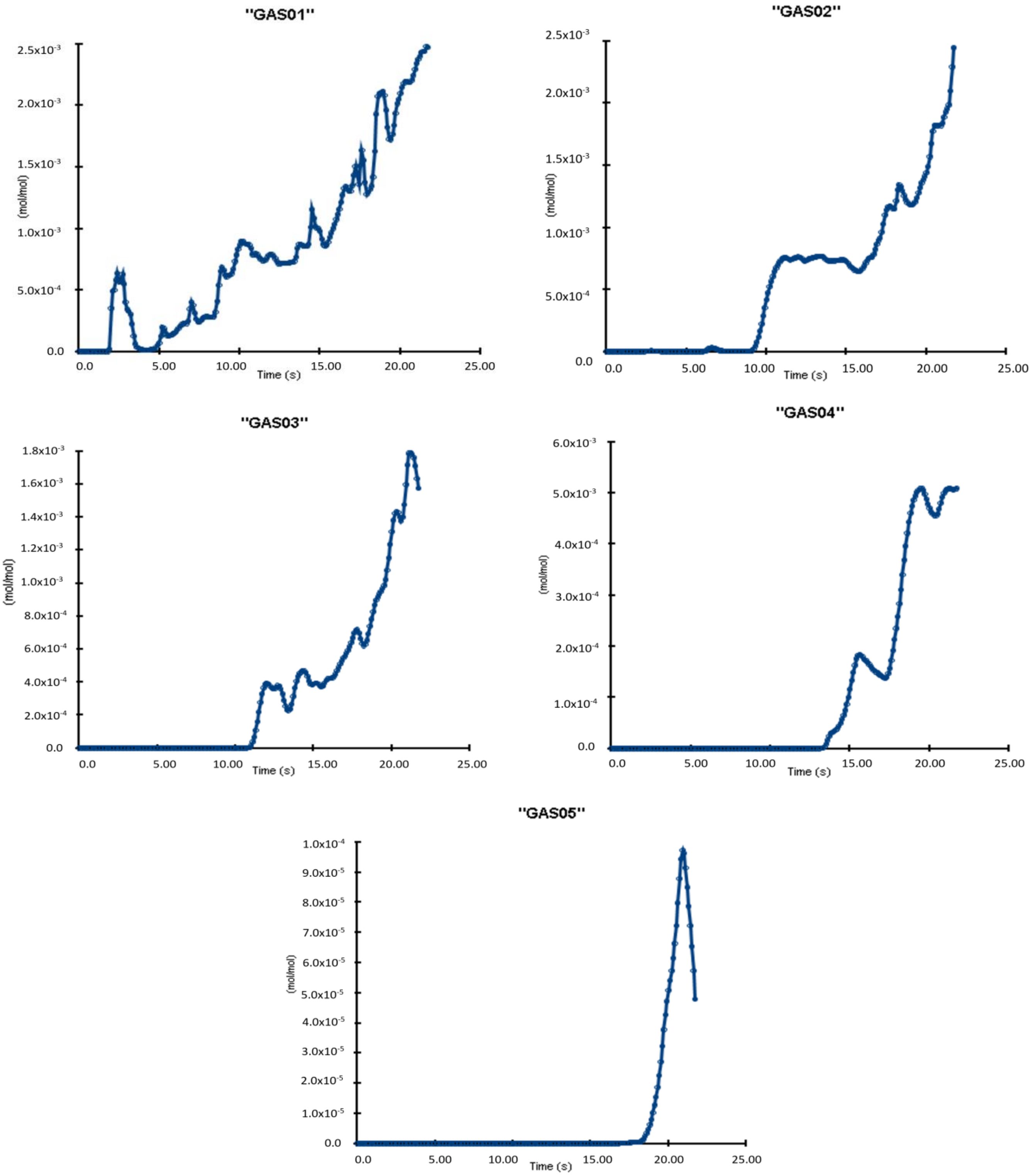


Figure 18. CO volume fraction diagrams (mol/mol).

The movement and penetration of smoke from the east wall (with the fire source) to the girls' locker room and stairwell occurred at approximately the same time as the power failure, due to the melting of the electrical conductors on the route indicated by the owner (the route of the electrical cable supplying the lighting fixture in the locker room was laid in a PVC cable channel on the walls of the entire floor, with the power supply coming from a cable running up the wall) and as evidenced by the testimony of a surviving witness (Figure 19).

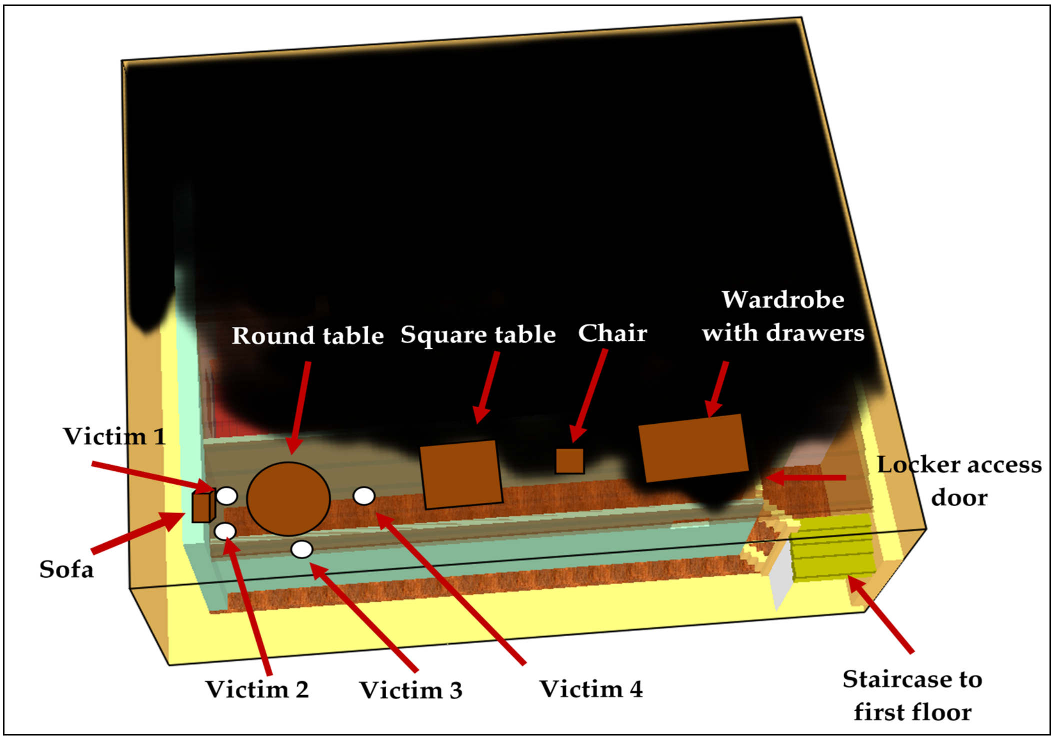


Figure 19. The advance of smoke and toxic gases from the wall with the fire source towards the locker room and the access staircase to the first floor.

4. Discussion

Comparing the two computer scenarios of the event, based on the interpretations of the temperature and carbon monoxide charts and given the higher values recorded for scenario 1 (temperature on sensor 1 was approximately 1100 °C, compared to 900 °C in the case of scenario 2 and the carbon monoxide concentration of 0.45% measured by sensor 1, compared to 0.25% in the case of scenario 2, noting that these values were recorded after about 30 s of running the simulation software; in the real situation, the values of carbon monoxide concentrations reached values of the order of volume percent due to the long burning time and the number of combustible materials involved in the event), it can be stated that the event was caused by the ignition of the fir wood beam supporting the floor of the separation floor between the ground floor and the first floor at the unblocked opening (identified on-site in the brick chimney), at a height above the bread oven connection. Confirmation of Scenario 1 is supported by the testimony of the fourth victim, who was rescued in time (regarding the appearance of toxic gases and smoke), and that of the owner (regarding the destruction of the PVC cable channel in the locker room).

The analysis of the event was carried out based on the data and material evidence found during the on-site investigation and developed in the article, in conjunction with the effects of CO concentrations on the human body, the testimony of the surviving victim, and the witnesses interviewed. Considering these elements, and following the technical scientific reasoning (such as the disorientation, fainting, an inability of the persons intoxicated with carbon monoxide to self-rescue (objective requested by the prosecution authorities)), the difficult observation on the fire on the floor, where there were no customers, the lack of visibility for the four victims, due to the absence of any window in the locker towards the bar area, and the rapidity of the fire's spread, led to the necessity of carrying out a computer simulation for the initial phase and the fire's development only at the first floor.

The most likely theory (hypothesis 1—the ignition of the wooden beam spanning the brick chimney through which the hot gases and incandescent particles from the flour used to cover the bread tray were discharged, the oven being a modified artisanal one with injectors on gas without protecting the bakery products) was supported by the observations made on the scene regarding the effects of the event, the claims made by the employees who asserted that they used the oven on the day in question, and the data collected from the surviving victim statement. For hypothesis 2, it was decided that it was appropriate to keep the same hot gases and incandescent particles from the flour used to cover the bread tray as a source of ignition, but positioned outside the building, came into contact with the polystyrene that was used to cover the walls. This hypothesis was based on the identification of the non-conformity of the flexible, non-self-supporting metal tube (Figure 3b,c). According to this theory, the fire's progression within the bar and the CO concentrations in the changing area show lower values than in the case of hypothesis 1, which would have given the rescuers enough time to evacuate all the victims confined in the dressing room.

5. Conclusions

A crucial tool in the technical scientific and forensic investigation of this kind of unwanted event is represented by computational fire modeling. The task of developing virtual models and computer simulations is easier in a case of a post-event fire investigation than it is in fire safety design engineering, because, in most cases, there is more information available about the incident from both the involved witnesses, photo-video recordings taken by the surveillance cameras, as well as from the analysis of the evidence gathered on-site, the firefighter's reports, etc.

One of the main applications of fire numerical modeling is hypothesis testing, which is a major step in the scientific analysis of fire. The hypothesis can be built not just to determine the causes of the event but also to identify the correct location of fire ignition, and hence the circumstances that contributed to or promoted its occurrence. Numerical models can contribute to the validation or rejection of statements, hypotheses, or assumptions by conducting multiple computer simulations for different fire scenarios. FDS is currently one of the most significant and popular analysis software tools, with excellent application in researching these events due to its advanced features.

The case study given demonstrates the relevance of applying numerical modeling and computer simulation in the time-consuming process of investigating fire events. The simulation findings were able to provide useful information on the process of fire initiation and development, as well as the distribution over time of temperature and carbon monoxide concentration in the examined space. Based on these findings, it was feasible to substantiate the testing of the two hypotheses of the investigators concerning the fire source and the way of initiation, and to determine which was the most likely.

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References

1. National Fire Protection Association. *NFPA 921 Guide for Fire and Explosion Investigations*; National Fire Protection Association: Quincy, MA, USA, 2021; ISBN 978-145590021-3.
2. Zhang, G.; Zhou, X.; Zhu, G.; Yan, S. A New Accident Analysis and Investigation Model for the Complex Building Fire Using Numerical Reconstruction. *Case Stud. Therm. Eng.* **2019**, *14*, 100426. [CrossRef]

3. Gorbett, G.E. Computer Fire Models for Fire Investigation and Reconstruction. *Int. Symp. Fire Investig. Sci. Technol.* **2008**, 23–34.
4. Farouk Abdel Gawad, A. Prediction of Smoke Propagation in a Big Multi-Story Building Using Fire Dynamics Simulator (FDS). *Am. J. Energy Eng.* **2015**, *3*, 23–41. [CrossRef]
5. Stauffer, E.; Dolan, J.A.; Newman, R. *Fire Debris Analysis*; Academic Press: Cambridge, MA, USA, 2008.
6. Lentini, J.J. *Scientific Protocols for Fire Investigation*, 3rd ed.; CRC Press: Boca Raton, FL, USA, 2018.
7. INSEMEX Petroșani. *The Technical Expertise of the Event Produced on 04/05/2014 at the Building Located on Tomis Boulevard No. 122 from the Municipality of Constanța*; INCD INSEMEX: Petrosani, Romania, 2014.
8. McGrattan, K.; Hostikka, S.; McDermott, R.; Floyd, J.; Weinschenk, C.; Overhold, K. *Sixth Edition Fire Dynamics Simulator User 's Guide (FDS)*; National Institute of Standards and Technology: Gaithersburg, MD, USA, 2022; Volume 6.
9. Gawad, A.A.; Albis, K.A.; Radhwi, M.N. Fire Dynamics Simulation and Evacuation for a Large Shopping Center (Mall): Part I, Fire Simulation Scenarios. *Am. J. Energy Eng.* **2015**, *3*, 52–71. [CrossRef]
10. Ling, D.; Kan, K. Numerical Simulations on Fire and Analysis of the Spread Characteristics of Smoke in Supermarket. In *Advanced Research on Computer Education, Simulation and Modeling. CESM 2011. Communications in Computer and Information Science*; Springer: Berlin/Heidelberg, Germany, 2011; Volume 176.
11. Li, D.W.; Zhang, J.Z. Numerical Analysis on Parameters Adjustment of Smoke Control System in a Complicated Underground Commercial Zone. In Proceedings of the 2nd International Conference On Systems Engineering and Modeling (ICSEM 2013), Beijing, China, 21–22 April 2013; Atlantis Press: Paris, France, 2013; Volume 341–342.
12. Gannouni, S.; Ben Maad, R. Numerical Analysis of Smoke Dispersion against the Wind in a Tunnel Fire. *J. Wind Eng. Ind. Aerodyn.* **2016**, *158*, 61–68. [CrossRef]
13. Hu, L.H.; Huo, R.; Peng, W.; Chow, W.K.; Yang, R.X. On the Maximum Smoke Temperature under the Ceiling in Tunnel Fires. *Tunn. Undergr. Sp. Technol.* **2006**, *21*, 650–655. [CrossRef]
14. Verda, V.; Borchiellini, R.; Cosentino, S.; Guelpa, E.; Tuni, J.M. Expanding the FDS Simulation Capabilities to Fire Tunnel Scenarios Through a Novel Multi-Scale Model. *Fire Technol.* **2021**, *57*, 2491–2514. [CrossRef]
15. Hassan, M.K.; Hossain, M.D.; Gilvonio, M.; Rahnamayiezekavat, P.; Douglas, G.; Pathirana, S.; Saha, S. Numerical Investigations on the Influencing Factors of Rapid Fire Spread of Flammable Cladding in a High-Rise Building. *Fire* **2022**, *5*, 149. [CrossRef]
16. Chen, T.B.Y.; Yuen, A.C.Y.; Yeoh, G.H.; Yang, W.; Chan, Q.N. Fire Risk Assessment of Combustible Exterior Cladding Using a Collective Numerical Database. *Fire* **2019**, *2*, 11. [CrossRef]
17. Tidwell, J. The Station Nightclub Fire: Revisiting the Lessons. *Fire Eng.* **2012**, *165*. Available online: https://www.fireengineering.com/firefighting/station-nightclub-fire-revisiting-lessons-full/#gref (accessed on 9 October 2022).
18. Bryner, N.; Madrzykowski, D.; Grosshandler, W. Reconstructing the Station Nightclub Fire—Computer Modeling of the Fire Growth and Spread. In Proceedings of the 11th International Interflam Conference, London, UK, 3–5 September 2007.
19. Yeh, C.T.; Shih, S.J.; Chi, J.H.; Shu, C.M. Thermal Hazard Analysis of ALA Nightclub Fire Debris. *J. Therm. Anal. Calorim.* **2014**, *117*, 1065–1071. [CrossRef]
20. Ciambelli, P.; Malangone, L.; Russo, P.; Vaccaro, S. Preliminary Modelling Study of Wildland Fires by WFDS. In Proceedings of the VI International Conference on Forest Fire Research, Coimbra, Portugal, 15–18 November 2010.
21. McGrattan, K.B.; Hamins, A.; Stroup, D.W. *International Fire Sprinkler, Smoke and Heat; Draft Curtain Fire Test Project—Large Scale Experiments and Model Development*; NISTIR: Gaithersburg, MD, USA, 1998. [CrossRef]
22. Cicione, A.; Beshir, M.; Walls, R.S.; Rush, D. Full-Scale Informal Settlement Dwelling Fire Experiments and Development of Numerical Models. *Fire Technol.* **2020**, *56*, 639–672. [CrossRef]
23. McGrattan, K.; Hostikka, S.; McDermott, R.; Floyd, J.; Weinschenk, C.; Overholt, K. *Sixth Edition Fire Dynamics Simulator Technical Reference Guide Volume 3: Validation*; NIST: Gaithersburg, MD, USA, 2020; Volume 1. [CrossRef]
24. Quintiere, J.; Torero, J.; Long, R. Material Fire Properties. *Adv. Mater. Proc.* **1998**, *10*, 1–14.
25. Quintiere, J.G. *Principles of Fire Behavior*; CRC Press: Boca Raton, FL, USA; Taylor & Francis Group: Abingdon, UK, 2016.
26. Hamins, A.; Maranghides, A. Report of Experimental Results for the International Fire Model Benchmarking and Validation Exercise# 3. *NIST Spec.* **2003**, *3*, 145.
27. Cho, C. *ME 4320-Thermodynamics II*; Western Michigan University: Kalamazoo, MI, USA, 2015.
28. The Engineering ToolBox. Available online: https://www.engineeringtoolbox.com/material-properties-t_24.html (accessed on 24 September 2022).
29. Purser, D.A.; Mc Allisterr, J.L. Assessment of Hazards to Occupants from Smoke, Toxic Gases, and Heat. In *SFPE Handbook of Fire Protection Engineering*, 5th ed.; Hurley, M.J., Ed.; Springer: Berlin/Heidelberg, Germany, 2016; pp. 2308–2428. ISBN 9781493925650.
30. *Acute Exposure Guideline Levels for Selected Airborne Chemicals*; National Academies Press: Washington, DC, USA, 2010; ISBN 978-0-309-14515-2.