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Comparative simulation of a fire in a paint storage warehouse: with and without an ESFR sprinkler system

Simularea comparativă a unui incendiu într-o hală de depozitare cu vopseluri: cu și fără sistem de stingere ESFR

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Abstract. *The paper presents a comparative analysis of two fire scenarios simulated using PyroSim, within a 7050 m² warehouse designated for paint storage. The first scenario excludes the activation of the ESFR sprinkler system, while the second evaluates its efficiency. Parameters such as heat release rate and temperature distribution are monitored. The results show a significant reduction in peak temperature (from 970 °C to 135 °C) and fire intensity, highlighting the essential role of sprinkler systems in limiting fire spread, protecting assets, and ensuring personnel safety.*

Key words: *PyroSim, Fire Dynamics Simulator, ESFR sprinklers, fire, warehouse*

Rezumat. *Lucrarea analizează comparativ două scenarii de incendiu simulate cu PyroSim, într-o hală de 7050 m² destinată depozitării vopselurilor. Primul scenariu nu include activarea sistemului de sprinklere ESFR, iar al doilea evaluează eficiența acestuia. Sunt urmăriți parametri precum rata de eliberare a căldurii și distribuția temperaturii. Rezultatele evidențiază o reducere considerabilă a temperaturii maxime (de la 970 °C la 135 °C) și a intensității incendiului, subliniind rolul esențial al sistemelor cu sprinklere în limitarea propagării, protejarea bunurilor și siguranța personalului.*

Cuvinte cheie: *PyroSim, Fire Dynamics Simulator, sprinklere ESFR, incendiu, deposit*

1. Introducere

PyroSim is an advanced software for fire simulation and is designed as a complementary tool to Fire Dynamics Simulator (FDS), a software created by the

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National Institute of Standardization and Technology. SDS models were created to reproduce phenomena such as smoke propagation, temperature variations, carbon monoxide concentrations, and other products resulting from fires [1]

Two fire scenarios will be developed that will include the start of a fire following the ignition of paint cans, placed on racks, in a storage hall, which has an area of 7050 m2.

Determining the heat load is a mandatory step in the analysis of fire scenarios. In the present case, an average calorific value of the paints of 33 MJ/kg was considered, which leads to a total heat load of 22,102,542 MJ and a specific heat load of 3,135 MJ/m² for the surface of the analyzed hall, according to Table 1.

Table 1

Features of stored materials

Material	Mass - Mi [kg]	Calorific value - Qi [MJ/kg]	Heat Load - SQ [MJ]	Area [sqm]	Thermal load - qs [MJ/sqm]
Paint	669774,00	33,00	22102542,00	7050,00	3135,11

Fire simulation involves the use of predefined parameters that describe the conditions inside the space affected by the fire. In this regard, the following characteristics have been established:

- Environment temperature: 20 degrees Celsius;
- Atmospheric pressure: 101325 Pa;
- Mass fraction of oxygen in ambient air: 0.2323 g/kg;
- Relative humidity: 40%;
- Gravitational constant: 9.81 m/s^2.

First scenario: the storage hall is monitored with a detection, signaling and warning system, but the ESFR sprinkler extinguishing system is not put into operation;

Second scenario: the storage hall is monitored with a detection, signaling and warning system and the ESFR sprinkler extinguishing installation will be activated.

Following the interpretation of the results obtained from the two fire scenarios, the efficiency of the ESFR sprinkler extinguishing installation in extinguishing fires produced at a paint storage hall will be evaluated, as well as the ability to intervene on the outbreak, both on the part of the specialized personnel and the first intervention teams.

2. Content of the paper

2.1 Description of scenario I

Scenario I aims to analyze and interpret the data resulting from the simulation that will render the development of the fire within **600 seconds**.

The event occurred on a working day, around 14:30, during normal working hours. There were 12 workers in the hall, and the main activity was the handling of paint containers, the stored substances being flammable. An employee used a makeshift extension cord to power a power tool. Due to an overload, an electric arc occurred, which ignited the accumulated vapors in the poorly ventilated work area. The flames spread quickly and ignited nearby materials. Shortly after the fire broke out, two workers tried to use portable fire extinguishers, but the flames were already too great, and the high temperature and dense smoke prevented them from approaching the outbreak. The automatic sprinkler extinguishing system did not work, due to a fault in the main valve, which was not reported and unchecked in recent months. Due to the stored substances, the fire generated large amounts of toxic smoke.

The 600-second interval was chosen considering the estimated time for equipping, moving and taking action of the intervention forces at the scene of the event. During this period, the phenomena produced by the fire are taken into account, as well as the analysis of the risks to which firefighters may be subjected during intervention operations to locate and extinguish fires.

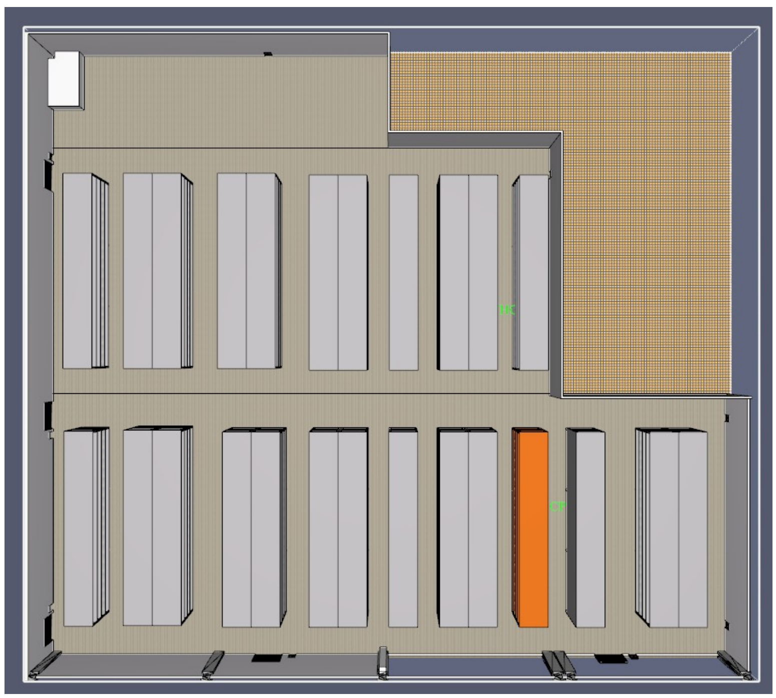

Fig. 1. Location of the fire outbreak

2.2 Description of scenario II

Scenario II aims to analyze and interpret the data resulting from the simulation that will render the development of the fire within **600 seconds**.

The event occurred under the same conditions: an employee used an improvised extension cord to power a power tool, and due to an overload, an electric arc occurred, which ignited the solvent vapor accumulated in a poorly ventilated area. Shortly after the fire broke out, the automatic sprinkler extinguishing system was activated, as a result of the high temperature detected in the affected area. The early activation of the sprinklers significantly reduced the intensity of the fire, limiting its spread to other areas of the hall.

Within this scenario, the evolution of temperature, smoke releases, flue gas movement and visibility are analyzed, in order to assess the impact of the parameters following the fire on the space in case of operation of the ESFR sprinkler extinguishing system.

Figure 2 shows the location of the sprinkler heads, which comply with the norms.

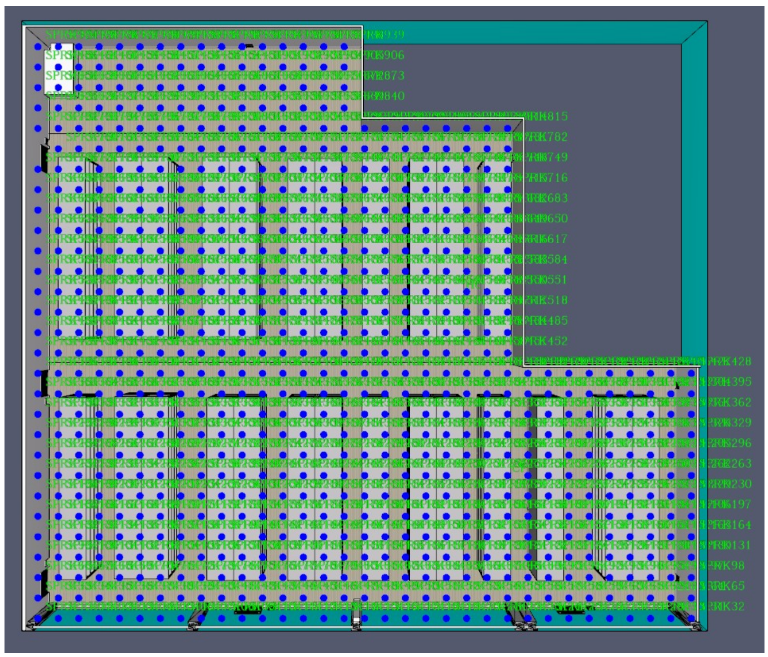

Fig.2. Location of sprinklers in the Pyrosim software

The characteristics of the sprinkler extinguishing system are multiple, but we extract the following characteristics:

- The technical solution for the installation: ESFR sprinkler extinguishing system;
- Maximum area covered by a sprinkler: $A_p = 9\ m^2$;
- Calculation density: $q_{is} = 7{,}65\ \frac{l}{s}$;
- Simultaneous Trigger Range: 108 m^2;
- Pressure: 3.6 bar;
- Volume of water reserve: 500 m^3;
- Sprinkler trigger temperature: 74 $^\circ$C;
- Installation height: 1.8 m

3. Results

3.1 Scenario I

1. Location of the firebox

The main objects subject to combustion in the storage hall are considered to be the solvent-based paint boxes and the racks on which they are placed (see Fig. 3.), having a weight of 932.4 kg/pallet generating a quantity of 3135.11 MJ/sqm.

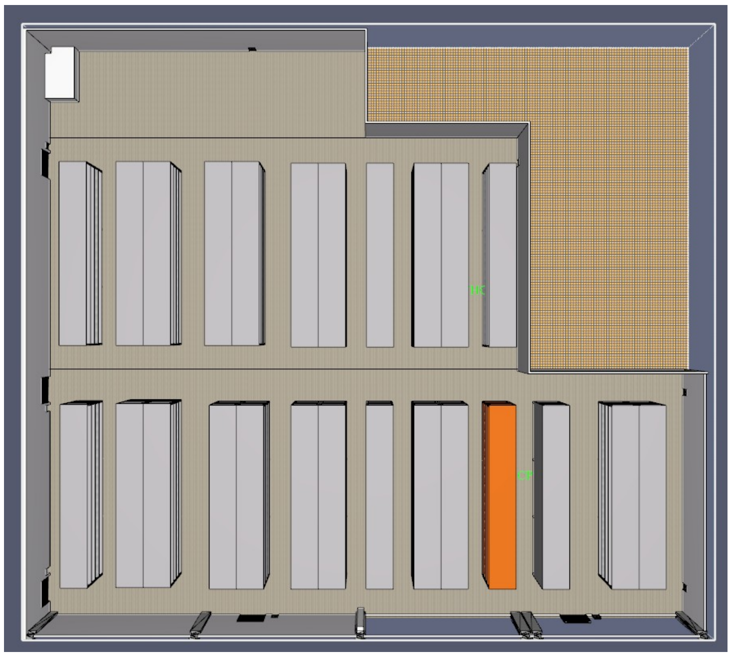

Fig. 3. Location of the fire outbreak

2. Temperature

In the simulation carried out with the PyroSim software, the temperature is one of the fundamental parameters for assessing the development of the fire and the thermal impact on the analyzed space. This is measured by means of thermocouple devices, located at various points in the space. The values obtained allow the observation of the thermal distribution and variation over time and highlight the rapid temperature increases in the vicinity of the focus and the propagation of heat.

The constant evolution of the firebox determines the appearance of thermal fluxes that are transmitted to the materials in the hall through the 3 types of heat transfer: radiation, conduction and convection.

Heat transfer is highlighted in Figure 4. by means of a horizontal plane placed at a height of 1.8 m from the floor. This value was chosen because the overall average height of adult males is 171 centimeters. Thus, the positioning of the analysis plane at this height allows the evaluation of the impact of thermal parameters on the airways, eyes and skull. Exposure to high temperatures can cause shortness of breath or dizziness.

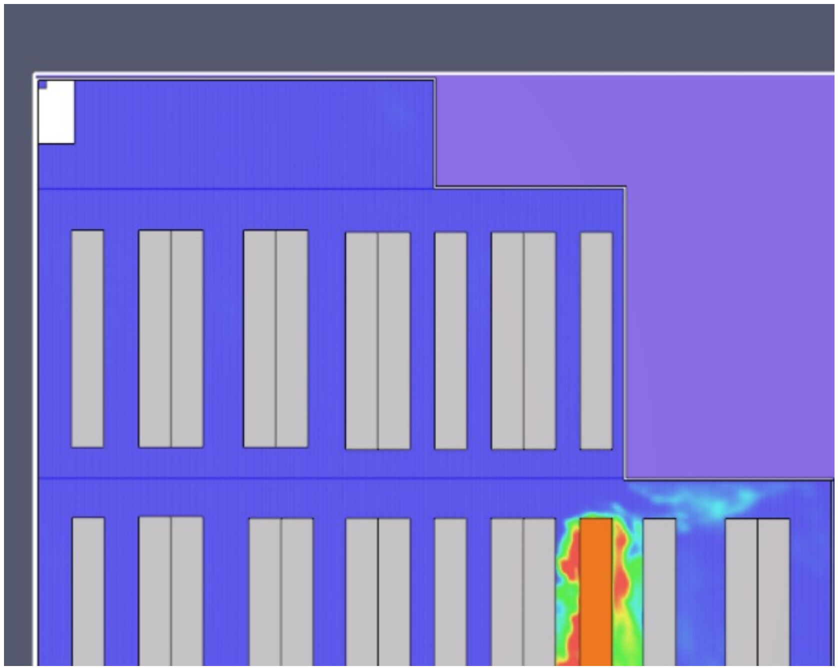

Fig. 4. Temperature variation in the hall for 600 seconds at a height of 1.8 m from the floor

It is observed that temperatures in the area of the outbreak start from 400°C and reach up to 970°C in the immediate vicinity.

In Fig. 5. The evolution of the temperature measured by the thermocouple located in the area of the firebox, 3 m from the floor, is presented. Following the analysis of the graph, an increase in temperature is observed in the range of 150-200 seconds, specific to the development phase of the fire. After reaching a value of about 1000° C, the temperature begins to oscillate slightly, as a result of the combustion of the combustible materials available in the combustion zone, and the heat energy input decreases.

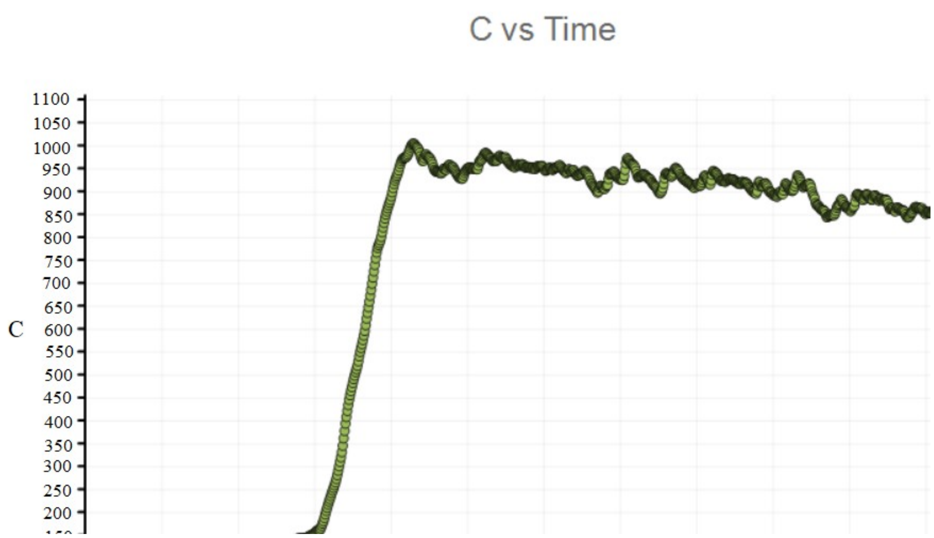

Fig. 5. The temperature measured by the thermocouple located in the area of the firebox

According to Figure 6, at the end of the 600 seconds, the temperature at the top of the hall in the outbreak area is around 970 °C.

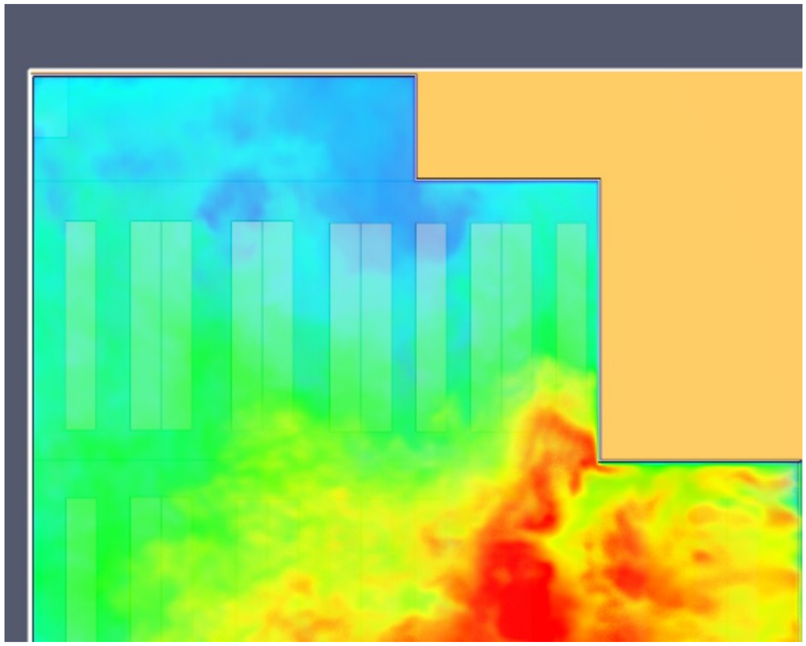

Fig. 6. Temperature at the top of the hall after 600 seconds

3. Flue gas movement

The combustion process, whether complete or incomplete, generates gases that influence the dynamics of the fire. The gases released from the combustion process have a lower density than the density of air and a higher temperature. These hot gases tend to rise rapidly vertically, moving towards the top of the room, after which they continue their movement horizontally, parallel to the ceiling. This phenomenon is essential in fire dynamics and has direct implications on visibility, exhaust conditions and heat transmission.

Figure 8 shows the movement and velocity of the flue gases in the storage hall. It is observed that in the area of the focus (shown in Figure 7) the speed of movement of the flue gases reaches values of up to 15 m/s, represented by the color red. The green color represents the areas where the speed of smoke movement has values of approximately 7.5 m/s. The blue color represents the areas where the speed has values of about 1.5 m/s or even lower, which happens in the corners of the hall, especially in those opposite the firebox.

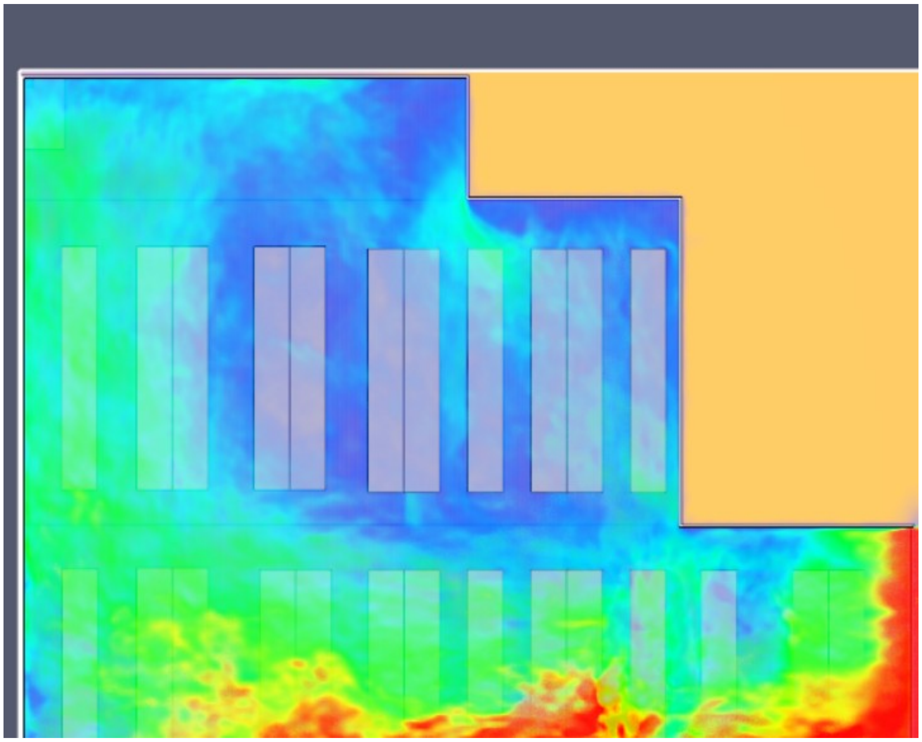

Fig. 7. Gas movement speed after 600 seconds at the top

4. Visibility within the hall

Visibility is a critical factor for assessing the evacuation and intervention conditions in the event of a fire in a storage hall. As the combustion of combustible materials generates dense smoke, the field of vision is significantly reduced, especially in the upper areas of the room. Low visibility affects the orientation of people inside, delays the evacuation process and can lead to panic. Also, low visibility negatively influences the efficiency of the intervention teams, which encounter problems in locating the outbreak or the victims.

Visibility of less than 10 metres is considered to significantly diminish the safe escape capacity [3].

Figure 8 shows the degree of visibility inside the hall at a height of 1.8 m from the floor. It is observed that, in the area of the outbreak, the visibility for the intervention personnel is non-existent, but they benefit from a degree of visibility on the left side of the space. Carrying out reconnaissance and locating the outbreak in the burned space are difficult, but not impossible. However, the high temperatures in the area of the burned space make the entry of the intervention crews dangerous.

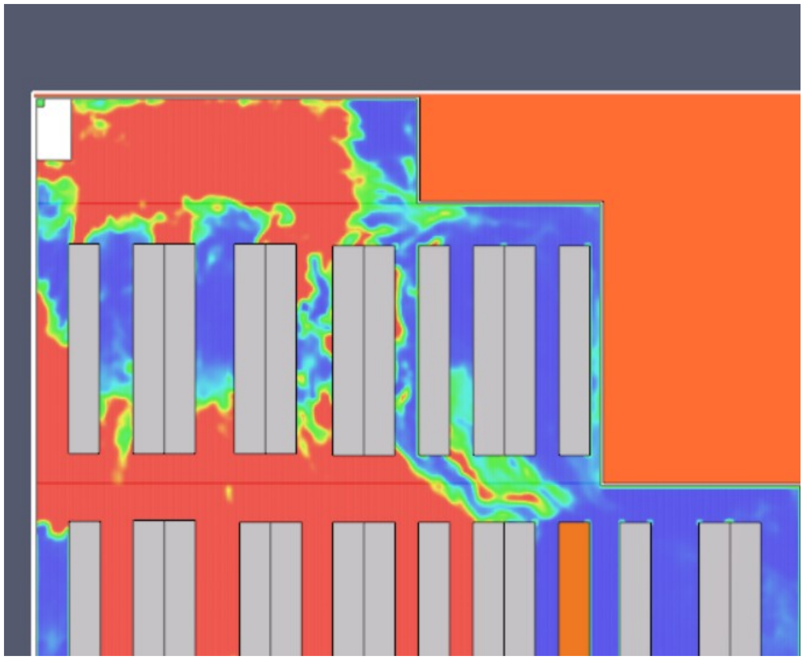

Fig. 8. Hall visibility after 600 seconds at a height of 1.8 m

Figure 9 shows the smoke stratification in the storage hall from different angles. Considering that the height of the hall is 12 m, it is observed that the smoke does not flood the entire hall vertically.

Fig. 9. Vertical smoke stratification after 600 seconds

3. Scenario II

1. Temperature

Figure 10 shows the temperature variation in the focus area, over a duration of 600 seconds, with the help of a thermocouple (THCP). The temperature in the area of the outbreak begins to rise rapidly and reaches a maximum value of about 1100° C. Subsequently, the temperature decreases, as a result of the entry into operation of the sprinkler system. However, the moment of commissioning of the installation does not correspond to reaching the maximum temperature, but only when the trigger temperature in the area of the sprinkler head is reached. Thus, the temperature reduction becomes visible only after a few seconds after the trigger, and the decrease is constant until the end of the analyzed interval.

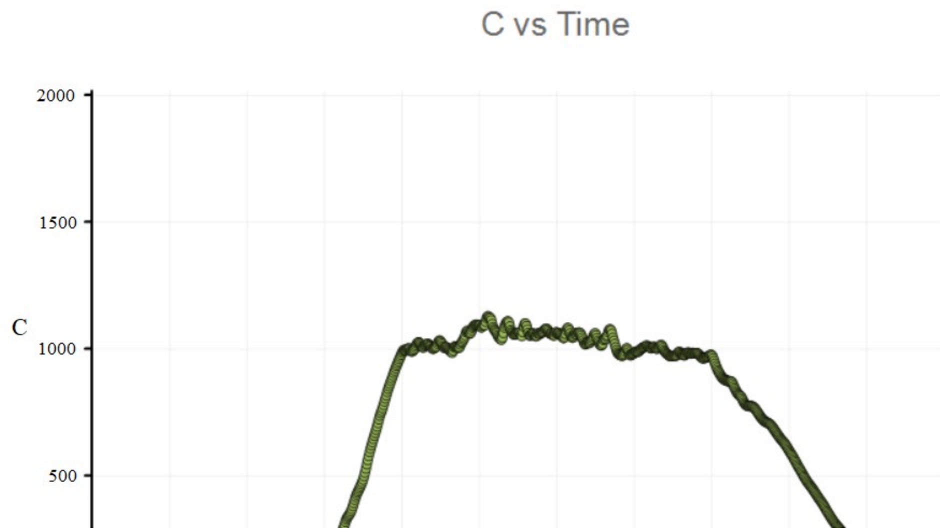

Fig. 10. The temperature measured by the thermocouple located in the area of the outbreak

The graph confirms the contribution of the sprinkler extinguishing installation in limiting the spread of the fire, even if the activation is not instantaneous. This underlines the importance of proper placement of the spinkler heads, for maximum efficiency in the early phase of the fire.

Figure 11, taken at the end of the 600 seconds, confirms the efficiency of the sprinkler installation in limiting the spread of the fire, the outbreak being efficiently controlled and completely extinguished.

These images confirm the role that sprinkler extinguishing systems play in limiting the spread of fire and reducing temperature.

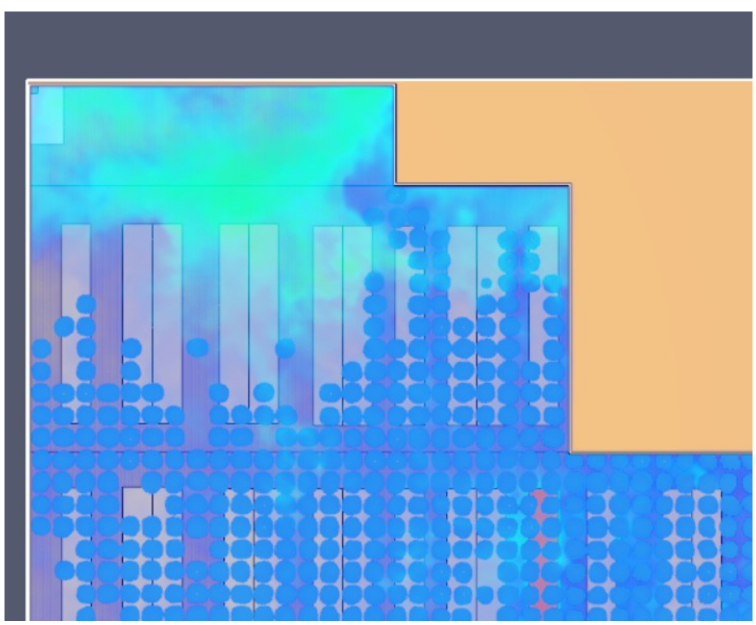
Fig. 11. Temperature in the ceiling area at the end of the 600 seconds

2. Flue gas movement

Figure 12 captures the moment a few seconds after the sprinkler installation is triggered, with the combustion process still active in the focus area. High flue gas velocities are observed, with values of 6.8 – 8.5 m/s, in shades of orange and red. These values signal the existence of strong currents that drive heat and smoke particles towards the ceiling, this stage being critical, because the gases contribute to the formation of the upper layer of smoke.

Figura 13 este realizată la finalul simulării, moment până în care acțiunea instalației de sprinklere și-a manifestat eficiența. Nuanțele albastre și verzi indică o scădere semnificativă a vitezi gazelor de ardere la nivelul plafonului, majoritatea valorilor fiind sub 2-3 m/s. Această reducere semnificativă evidențiază disiparea energiei acumulate și limitarea propagării incendiului.

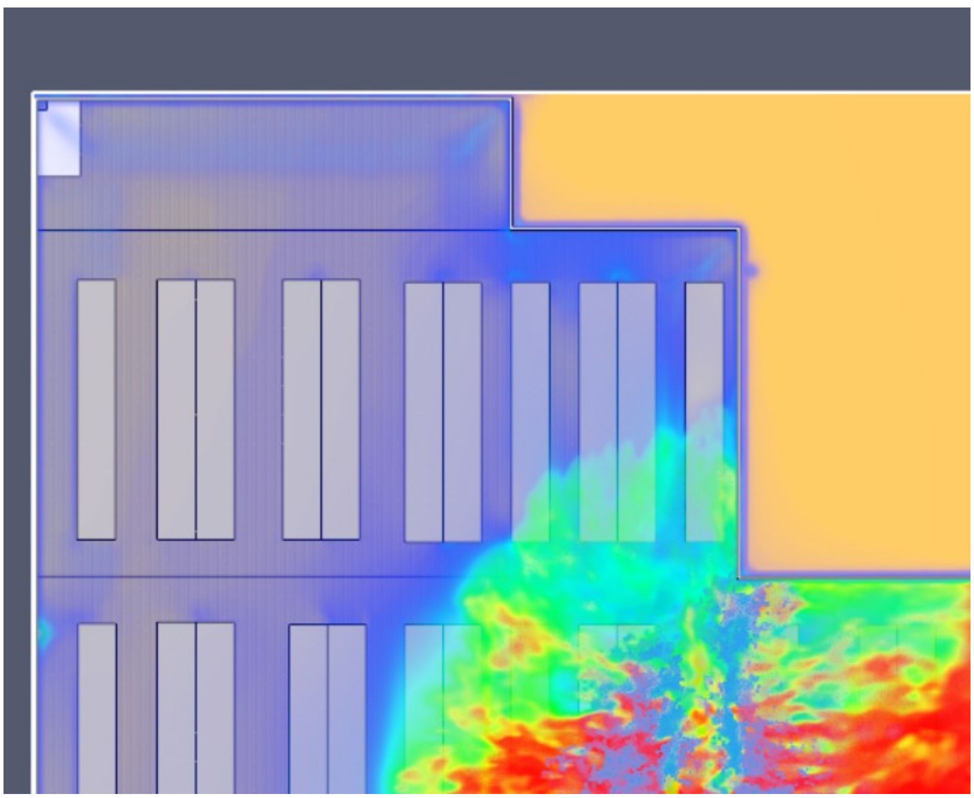

Fig. 12. Flue gas movement after sprinklers are triggered

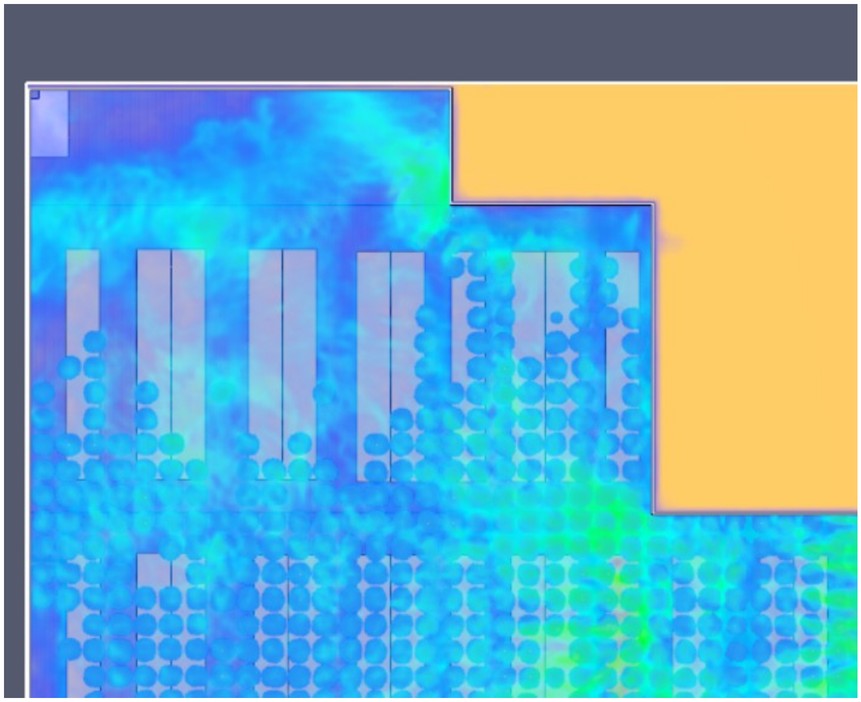

Fig. 13. Flue gas movement at the end of 600 seconds

3. Visibility within space

The images below show the visibility inside the hall at a height of 1.8 m from the floor, corresponding to the average level of the field of vision for an adult male.

Figure 14 shows a significant decrease in visibility in the area of the outbreak, caused by the accumulation of flue gases and dense smoke. Areas highlighted with shades of blue indicate visibility below 3 m, critical values that can affect people's orientation.

Fig. 14. Visibility inside the hall at a height of 1.8 m before the sprinklers are triggered

Figure 15 shows the situation at the end of the 600 seconds, after the sprinkler system has come into operation. In the area of the outbreak, visibility is almost non-existent, which is highlighted by the blue color. The central area allows good visibility, up to approx. 30 m.

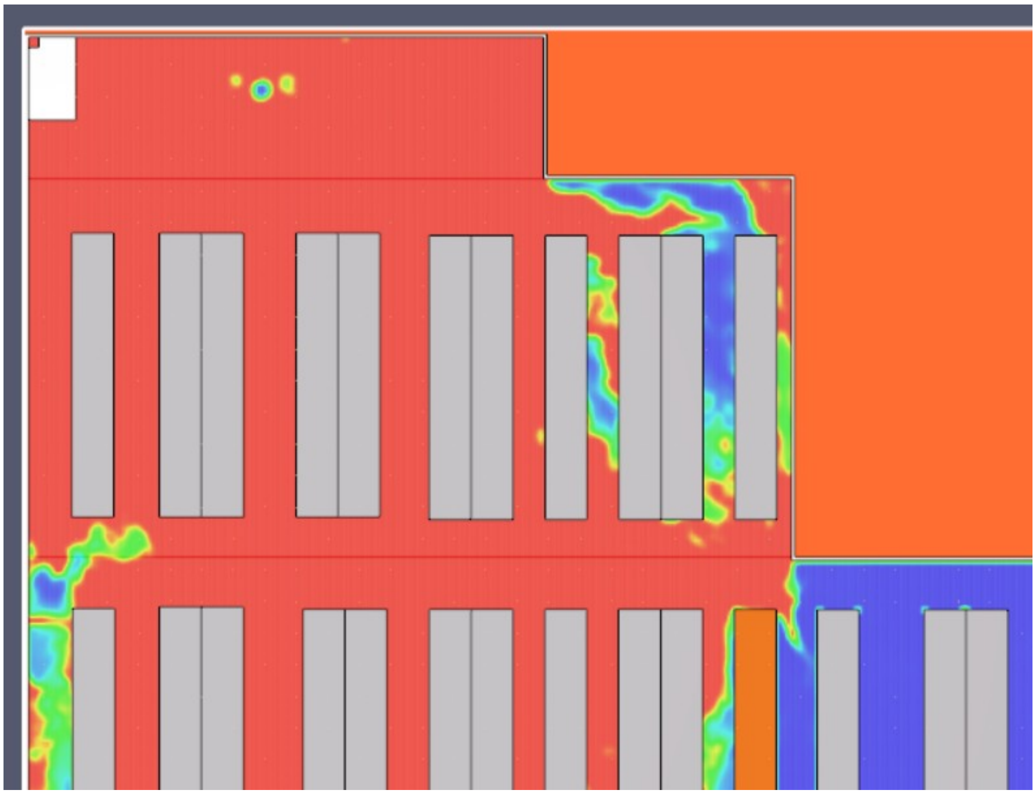

Fig. 15. Visibility inside the hall at a height of 1.8 m at the end of the 600 seconds

4. Discussions

The analysis of the characteristic parameters of the fire in the two scenarios is shown in Table 2.

Table 2

Comparing the results of the two simulations

Studied parameter	Simulation 600 seconds without the use of ESFR sprinkler extinguishing system	600-second simulation with the use of ESFR sprinkler extinguishing system
Temperature variation in the ceiling area	210°C – 970°C	60°C – 135°C
Temperature variation at a height of 1.8 m from the floor	400°C – 970°C	60°C – 105°C

Comparative simulation of a fire in a paint storage warehouse: with and without an ESFR sprinkler system

Studied parameter	Simulation 600 seconds without the use of ESFR sprinkler extinguishing system	600-second simulation with the use of ESFR sprinkler extinguishing system
Flue gas velocity	1.5 m/s – 15 m/s	0.85 m/s – 3.4 m/s
Visibility at a height of 1.8 m from the floor	0 m in the area of the firebox and the right side of the hall Up to 30 m on the left and central side of the hall	0 m – 15 m in the firebox area and the right side of the hall 15 m – 30 m in the central and left part of the hall
Smoke stratification	Complete flooding at ceiling level Partial flooding in the vertical plane	Complete flooding at ceiling level Partial flooding in the vertical plane

The analysis of the two scenarios, with and without the use of the ESFR sprinkler extinguishing system, highlights the efficiency of this system in the context of the active protection of a paint storage hall.

The commissioning of the installation causes a significant decrease in the maximum temperature recorded, both in the ceiling area and at a height of 1.8 m from the floor, which contributes to limiting the spread of fire and reducing the associated risks.

All these aspects underline the idea that the integration of an ESFR sprinkler installation not only limits the spread of fire, but also obviously contributes to the protection of property. This is an effective technical solution for industrial premises exposed to a high risk of fire.

5. Conclusions

Following the simulations carried out using PyroSim software, which analyzed fire behavior in two scenarios – one without the operation of the ESFR sprinkler system and one with its activation – the effectiveness of the automatic suppression system in limiting the effects of a fire in a paint storage hall was clearly demonstrated [4].

The scenario without sprinklers led to the development of a high-intensity fire, with extremely high temperatures (up to 970 °C at ceiling level). These conditions made human intervention impossible in the early phases and posed a significant risk to both personnel safety and the structural integrity of the building [5].

In contrast, the scenario in which the ESFR sprinkler system functioned correctly showed a substantial reduction in recorded temperatures, underlining the crucial role of this technology in rapid fire control. The activation of the system limited fire spread and reduced the thermal impact on both the structure and the occupants [6].

In conclusion, the implementation of ESFR sprinkler systems proves to be an essential solution for active fire protection in storage facilities with a high fire risk [7].

Referinţe

[1] "Fire Dynamics Simulator (FDS) Graphical Interface (GUI) for 3D Fire and Smoke Modeling: PyroSim." Accessed: July 19, 2025. [Online]. Available: https://www.thunderheadeng.com/pyrosim/

[2] M. Roser, C. Appel, and H. Ritchie, "Human Height," *Our World in Data*, May 2021, Accessed: July 19, 2025. [Online]. Available: https://ourworldindata.org/human-height

[3] Purser, D. A. Toxicity Assessment of Combustion Products. In: SFPE Handbook of Fire Protection Engineering, 5th Edition

[4] K. B. McGrattan, "Fire dynamics simulator (version 4): technical reference guide," *NIST Special Publication*.

[5] "NFPA | The National Fire Protection Association." Accessed: July 19, 2025. [Online]. Available: https://www.nfpa.org/en

[6] R. Peacock, "A Review of Building Evacuation Models: 2nd Edition".

[7] "(PDF) Numerical Simulation of Sprinkler Suppression of Rack Storage Fires," *ResearchGate*, doi: 10.3801/IAFSS.FSS.11-1170.