

CFD Simulation of Fire Dynamics in Textile Warehouses Using PyroSim and Fire Dynamics Simulator (FDS)

Simulare CFD a dinamicii incendiului în depozitele de textile folosind PyroSim și Simulatorul de dinamică a incendiului (FDS)

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Abstract. *This study investigates the use of Computational Fluid Dynamics (CFD) simulations, employing PyroSim and the Fire Dynamics Simulator (FDS), to analyze fire dynamics in a textile warehouse. The research focuses on modeling a specific fire scenario to assess fire propagation, temperature distribution, smoke movement, and visibility conditions. The results are intended to inform fire safety strategies and evaluate the effectiveness of existing fire prevention measures in such facilities*

Keywords: *PyroSim, Fire Dynamics Simulator, statistical analysis, fire simulation, warehouse*

1. Introduction

In recent years, the use of advanced computational simulations, such as those performed using the PyroSim software, has significantly improved the way fire safety engineering is approached. These simulations provide engineers with deeper insights into fire behavior, helping them make informed decisions and develop robust strategies that effectively protect both lives and property. Studies [1-3] have demonstrated the capabilities of FDS in predicting fire behavior in various building types. Applying CFD simulations to fires in textile warehouses comes with a set of challenges, due to the significant quantity of combustible materials, and the fast and unpredictable nature of fire spread in such environments. These complexities require careful consideration in modeling and interpreting simulation results to ensure accurate outcomes.

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Workspace definition for the present study

The first step in preparing a working model in PyroSim is to define the geometry through obstacles, represented by: floor, walls, support pillars, beams, ceiling, shelves, and in the case of each obstacle, to specify the nature of the material from which it is made is defined.

The building's resistance structure is designed to provide adequate fire protection and is built using fire-resistant materials and elements and it consists of:

- *Reinforced concrete frames* made of class A1 pillars, fire resistant for 120 minutes (R120), and class A1 beams, fire resistant for 45 minutes (R45).
- *The perimeter enclosures*, built of brick masonry with a thickness of 20-40 cm. This masonry is classified as A1, fire resistant for 240 minutes (REI240), providing an additional barrier against the spread of fire.
- *The floor* made of concrete, which ensures a strong and durable surface, also classified as A1, fire resistance.
- *The interior partitioning* between storage spaces with the same level of fire danger made of plasterboard-plasterboard with a thickness of 22 cm. These boards are classified as A2 - s1, d0, providing adequate protection against the spread of fire for 180 minutes (EI180).
- *Communication* within the same fire compartment is made through two fire-resistant doors with a fire resistance of 45 minutes (EI 45 - C), thus ensuring safety and fire insulation in the event of an emergency situation [4].

Fig. 1. Room geometry

Defining Fire

This step involves many engineering solutions based on the multitude of chemical reactions that can take place following the combustion process.

The outbreak can be achieved through two main components:

1. *Reaction:* parameters that define the combustion process and aim to define the way in which the molecules of atoms combine with each other to produce the by-products resulting from combustion and implicitly heat
2. *Surface:* parameters that define the physical and chemical characteristics of the combustible and non-combustible materials that go into the composition of the working model [5].

Size workspace-specific cells

As a general rule, the smaller the size of the cells that define the geometry of the model, the more the precision of the simulation increases, being as close to reality as possible. At the same time, this also leads to an increase in the running time of the program in order to process the data necessary to perform the analysis on the behavior of the existing combustion process.

This was done in order to obtain data that would express as much as possible the results of a fire in a real situation.

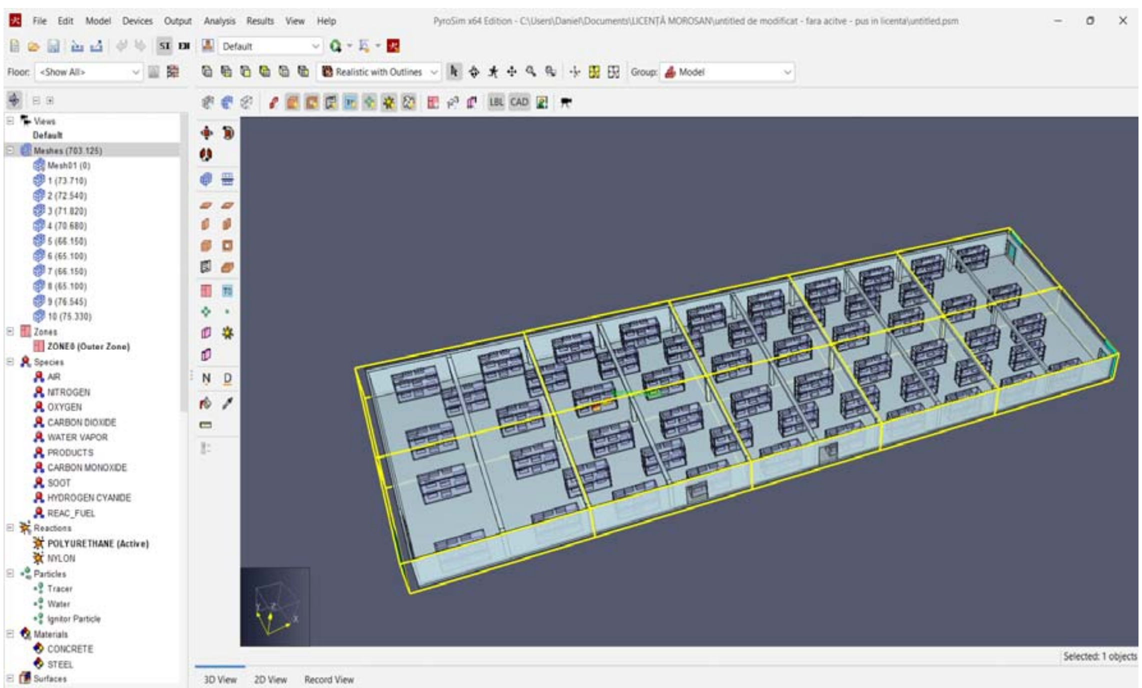

Fig. 2. Workspace Assignment

In order to establish a more detailed analysis of the fire parameters, 2D plans (slices) were introduced in the compartment.

These planes allow for the observation and interpretation of changes in temperature, visibility, and smoke movement velocity during the simulation.

By examining these plans at various points and at different points in the simulation, we can gain a deeper understanding of the evolution of the fire and its impact on the environment. This method helps us identify critical areas and develop effective fire response strategies.

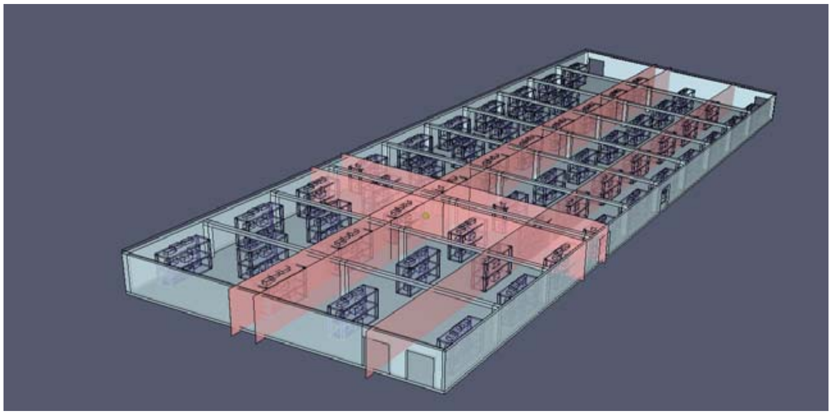

Fig. 3. Distribution of 2D planes

Definition of the simulation parameters:

There are many parameters that can be defined in Fire Dynamics Simulator (FDS), which influence the running time of the program depending on the duration of the fire simulation, radiation calculations, particle life, ambient configuration (temperature, pressure, concentration of gases in the air composition, humidity) [6].

The mesh resolution was selected based on a consideration of computational resources and the need to adequately resolve the key fire dynamics phenomena, particularly the flame height. A mesh sensitivity study was conducted to ensure that further refinement of the grid did not significantly alter the simulation results.

For the simulation, the following parameters of the ambient environment are established:

- Temperature: 20°C.
- Pressure: 101325 Pa.
- Mass fraction of oxygen: 0.2323.
- Relative humidity: 40%.
- Gravitational constant: 9.81 m/s^2

The particularities of the fire (temperature, visibility, smoke propagation in the respective space) will be analyzed for a period of 5-minutes, this time actually representing the duration until the intervention forces come into action according to the area of location of the warehouse within the intervention district specific to the detachment.

2. Scenario of the occurrence of the fire

The simulation focuses on a compartment intended for the storage of textile materials, in which the products are organized in boxes arranged on shelves, aligned in a single row. Inside this warehouse, there are about 60 tons of textiles and/or leather on an area developed by 1739.6 m^2.

Calculation of the thermal load [6,7]: The estimated thermal load of the compartment is determined according to the nature of the combustible materials present, as follows:

- According to MP008 Romanian norm *the calorific value* of finished textiles is:

$$Qi = 16{,}3\ Mj/kg.$$

- The thermal load of the storage space is:

$$60.000\ kg * 16{,}3\ Mj/kg = 978.000\ Mj$$

- The heat load density of the textile warehouse is:

$$\frac{978.000\ Mj}{1739{,}58\ m^2} = 562{,}2\ \frac{Mj}{m^2}$$

Fire risk: taking into account the purpose of the construction (textile warehouse), the fire risk is established in the case of production and/or storage buildings, thus resulting in a HIGH FIRE RISK [6,7].

Protection systems

The warehouse is subject to fire safety approval and/or authorization due to the developed area, which is greater than or equal to 600 sqm, in this case as 1739,6 sqm and as result the building must be equipped with active fire protection systems having [8,9]:

- indoor hydrant installations, being part of the category of fire limitation and extinguishing installations.
- fire detection, signaling and warning installations.
- hot gas smoke and exhaust installations for storage spaces with areas larger than 36 sqm.

The simulation scenario involves the negligence of an employee who throws a cigarette in the space, despite the strict smoking ban. The outbreak of the fire is initially formed in the packaging in which the textile products were kept, and the flames quickly spread to the adjacent boxes, thus creating an emergency situation.

Fortunately, the fire detection, signaling and warning installation worked at normal parameters, thus warning all the personnel in the building who managed to evacuate entirely and safely, thus there were no victims as a result of the emergency situation created. According to the reports of the own emergency intervention staff, the hydrant installation did not work with the supply valves stuck due to the lack of periodic maintenance, so the specific intervention staff had to evacuate, also noticing that the smoke extraction hatches were not opened. Thus, the worst case scenario was taken into consideration, to highlight the rapid spread of the smoke, even in the initial phase of the fire.

3. Interpretation and analysis of results

Based on the fire scenario, the analysis and interpretation of simulation results cover the first 5 minutes after ignition. This interval was selected because it represents the typical response time required for emergency services to arrive, allowing the study to effectively evaluate the conditions firefighters face upon entry.

At the same time, the non-functionality of the active fire protection systems in the facility's equipment (smoke extraction installation and indoor hydrant installation) will also be taken into account, due to various technical reasons caused by the lack of periodic maintenance.

The parameters of the fire are chosen according to their importance at the time of the firefighters' intervention, which lead to an increase or decrease in the degree of difficulty of the mission itself.

Temperature

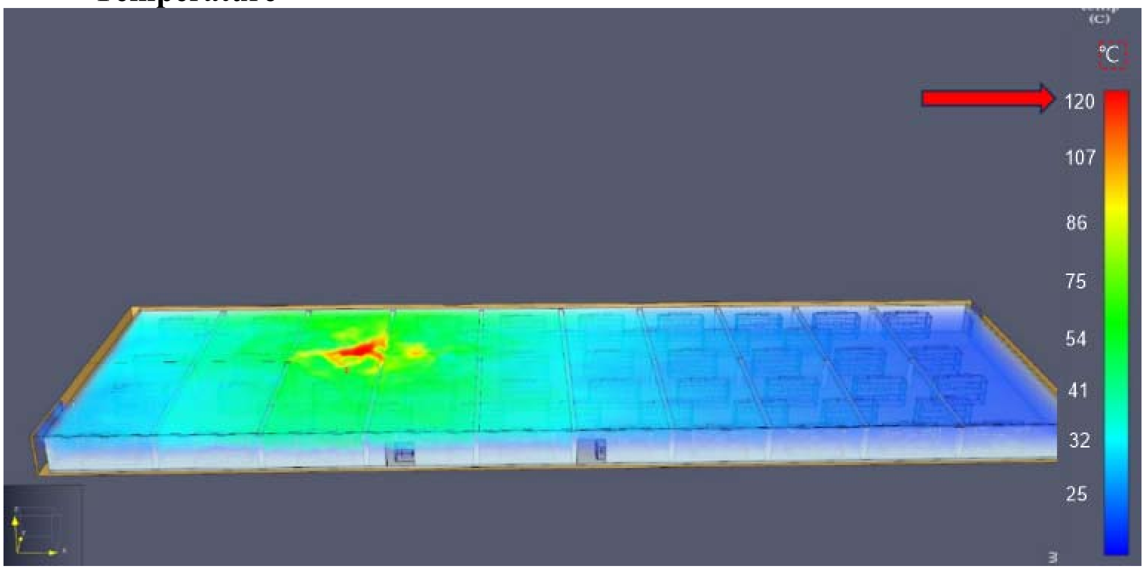

Fig. 4. Temperature of fire effluents

At ceiling level, in a fire compartment, the accumulated smoke and flue gases reach temperatures of over 120°C in the area of the firebox, after 5 minutes. This area is illustrated in Figure 4 in red. As the smoke moves horizontally over the entire surface of the ceiling, flooding the compartment, its temperature drops. This phenomenon is illustrated by the change in the color of the smoke to yellow, green and blue, respectively.

The ignition of textiles containing cotton involves the rapid transition from slow combustion to flame combustion. In the case of self-ignition, the carbonization of the inner layers occurs from a temperature of 160°C.

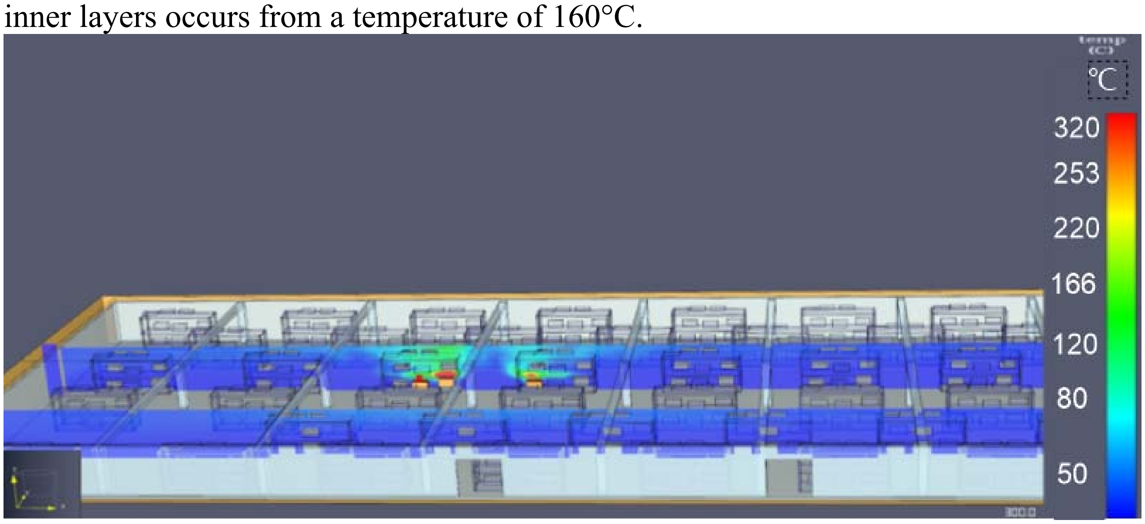

Fig. 5. Temperature in the area of the outbreak

On the other hand, synthetic fibers used in blends to make finished products have a lower fire hazard. These fibers melt under the action of heat. For example, nylon has a melting temperature between 200°C and 300°C [11].

Through experiments carried out, it has been shown that in the case of a combustion characterized by the presence of flames, about 70% of the energy generated by the fire is transferred to the environment through the convection process, while the remaining 30% is transmitted by radiation. This finding highlights the importance of the convection process in heat transmission in fires, where heated air rises and is replaced by cooler air, contributing to the spread and intensification of the fire [12-14].

Flue gas movement

In the absence of a smoke and hot gas evacuation system, the latter, being influenced by the upward force generated by the heat emanating during the fire, will rise vertically towards the ceiling of the room. Once in the ceiling area, the smoke will move horizontally towards the entire surface of the compartment, under the action of convection and turbulence.

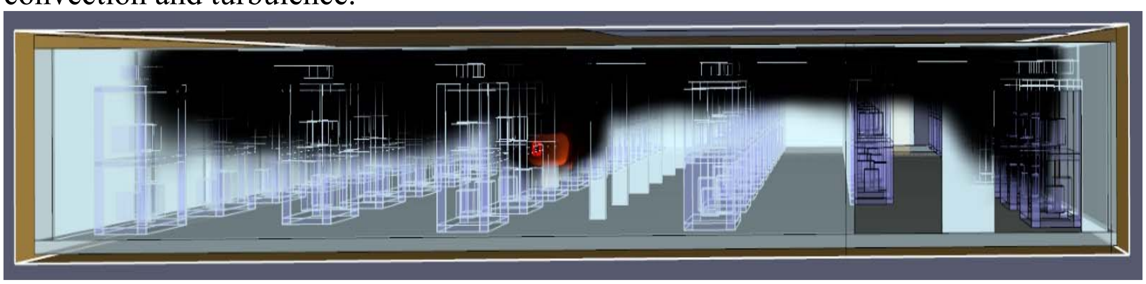

Fig. 6. Smoke stratification in the warehouse after 30 seconds

In this phase, the smoke forms a dense and coarse stratification that extends over the entire surface of the ceiling.

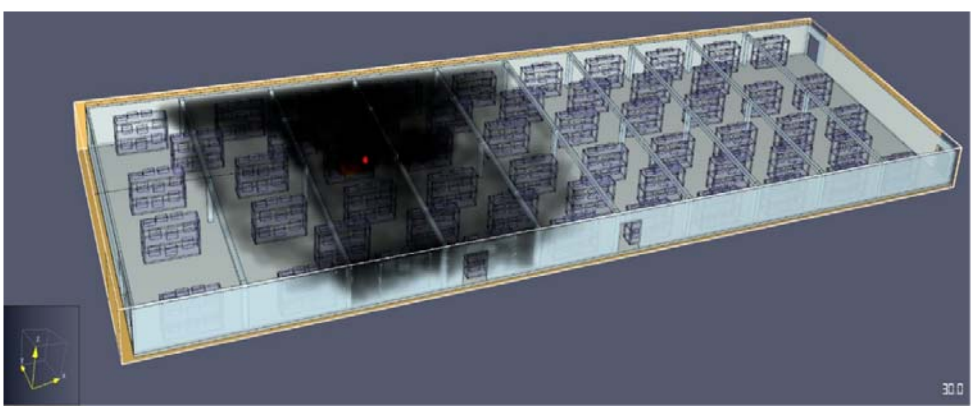

Fig. 7. Smoke propagation in the warehouse after 30 seconds

Fig. 8. Smoke propagation in the warehouse after 5 minutes

So, as can be seen from Figures 7 and 8, after 5 minutes the warehouse is flooded with smoke, greatly reducing visibility and making it difficult for firefighters to intervene.

Following the fire, due to the upward force generated by the heat emanating from the fires, the smoke and hot gases move vertically at a speed of around 1.5 meters per second, according to the indications shown in Figure 9, illustrated by a distinctive red color. Once they reach the top of the space, the smoke and flue gases slow down and begin to expand horizontally across the ceiling surface.

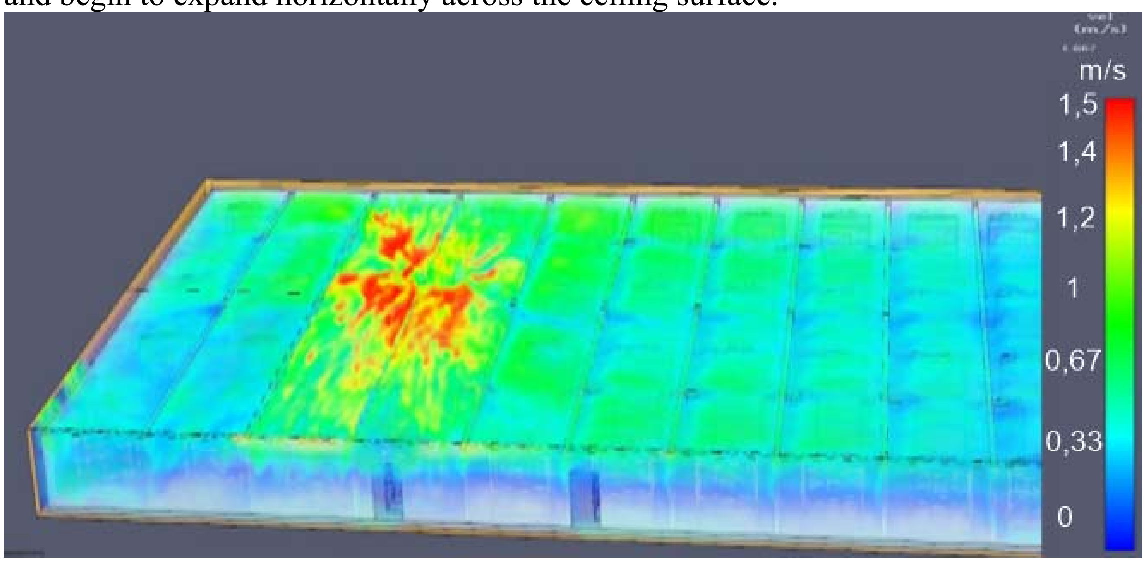

Fig. 9. Speed of smoke movement in the burned space after 5 minutes

As a result, the entire area of the warehouse is flooded with smoke, generating a dangerous situation in terms of safety and evacuation.

Factors influencing the rate of fire growth:

- *the amount of combustible dust* (such as in the textile or woodworking industry)
- *ventilation* because in closed spaces with low ventilation, the accumulation of smoke and heat is favored, accelerating the spread of the fire.
- *the composition of combustible materials* because fast-burning materials (such as textiles) will contribute to a faster spread of the fire

Visibility within the warehouse

Smoke stratification and vertical visibility:

- In an enclosed space, the smoke resulting from combustion tends to stratify, i.e. to accumulate in the upper part of the room.
- The smoke layer can greatly reduce vertical visibility. In many cases, vertical visibility can be completely lost in about 2 minutes.

It is important to emphasize that this aspect can become a significant threat to the safety of people and the building due to obstruction of visibility, increase in temperature and concentrations of toxic substances.

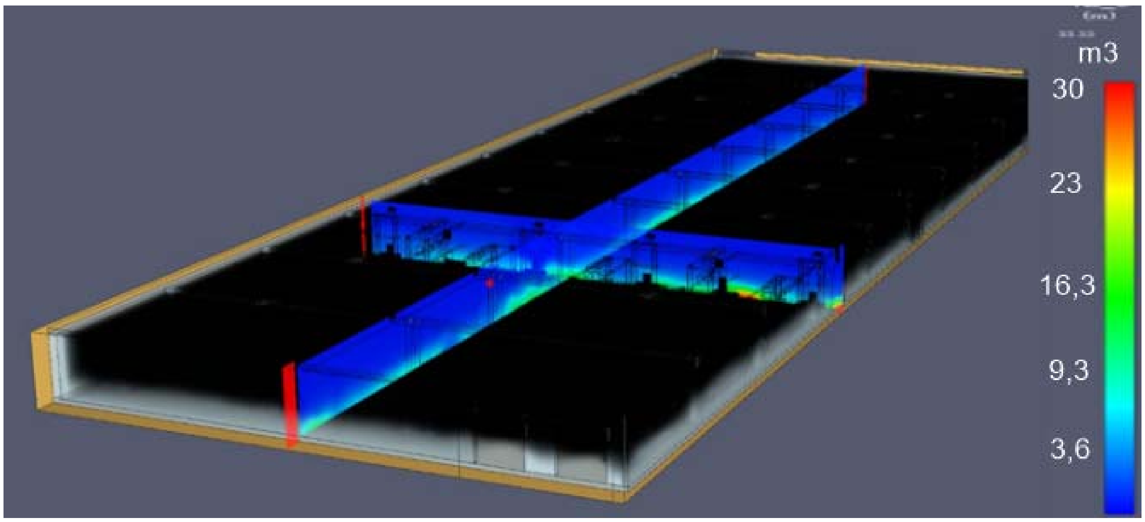

Fig. 10. Visibility in the warehouse at the time of the firefighters' intervention (5 minutes)

4. Conclusions

The use of simulations in the PyroSim program facilitates the obtaining of a general engineering perspective, clearly highlighting the parameters investigated in order to meet the fire safety requirements of the warehouse.

For the present study, the following values were obtained:

- maximum temperature of the fire effluents in the ceiling area, 120 °C.
- maximum temperature in the focus area, 320 °C.
- flue gas velocity around 1.5 m/s.

Visibility at the upper levels of the warehouse drops rapidly, becoming completely obscured within minutes due to heavy smoke accumulation. As time progresses, smoke gradually fills the entire space, significantly reducing visibility even at ground level by the 5-minute mark. This severely complicates firefighting efforts, making it difficult for intervention teams to navigate and perform rescue operations.

This study highlights the value of using CFD simulations to gain insights into fire dynamics within textile warehouses, together with improving fire safety strategies.

Future research should consider additional fire scenarios and perform detailed Heat Release Rate (HRR) analyses under varying conditions to study the heat transfer.

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