RATIONALE FOR THE USE OF UAV SYSTEMS IN THE MANAGEMENT OF MAJOR INDUSTRIAL FIRES THROUGH FLUID DYNAMICS MODELING

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DOI: 10.19062/2247-3173.2026.27.14

Abstract: *The present paper evaluates the efficiency of UAV systems in suppressing fires in industrial warehouses, a complex environment characterized by high thermal loads and severe limitations for human intervention. The main objective is to demonstrate the capability of drones to stabilize environmental parameters and to define the optimal technical requirements for their development. The study employs computational modeling using the PyroSim software to simulate the dynamics of a fire in an industrial warehouse. The methodology is based on the comparison of two scenarios: the natural evolution of a free-burning fire and the active intervention of a group composed of four drones. The analysis of the results confirms that the action of UAV systems effectively manages thermal energy, reducing the maximum temperature at ceiling level from 270°C to a controlled level of 120°C. This cooling prevents excessive accumulation of hot gases, protects the structural integrity of the building, and maintains optimal visibility at ground level. A major advantage of this research lies in the use of the extracted data to determine the operational parameters of the drones, demonstrating the utility of simulations as a basis for designing equipment adapted to challenging environments. In conclusion, the paper validates the operational performance of UAV groups as an optimal solution for limiting fire sources and highlights the importance of numerical modeling as an essential tool for risk prediction, eliminating the need for direct exposure of intervention personnel in critical situations.*

Keywords: *simulation, UAV, fire, industry, innovation.*

1. INTRODUCTION

Technological development in the industrial environment has led to an increase in the complexity of critical infrastructures, where the high concentration of flammable materials requires proactive and dynamic fire risk management [1–3]. In the early stages of a major event, access for intervention forces is often obstructed by lethal levels of thermal radiation and the risk of structural collapse [4]. In this context, these limitations necessitate a transition toward tactical solutions, such as the use of UAV (Unmanned Aerial Vehicle) systems capable of delivering direct discharge of extinguishing agents in the vicinity of the fire source [5].

2. FIRE DYNAMICS IN THE INDUSTRIAL ENVIRONMENT

Industrial fires are characterized by high thermal intensity and the generation of large quantities of smoke and toxic gases, these factors being determined by the significant fire load and the specifics of storage [6].

Another fundamental characteristic is the scale of development, which may generate severe consequences for the environment, adjacent critical infrastructure, and the population [7].

The dynamics of these fires are conditioned by a series of variable parameters: the nature of combustible materials, the spatial configuration of storage, the density of the thermal load, and the building volume, elements that determine the rate of fire spread. Due to the technological diversity of storage systems, these events exhibit atypical and highly dynamic development patterns.

From the perspective of size and heat release rate (HRR), the management of such situations requires the deployment of substantial human resources to limit propagation toward neighboring structures. Fire spread occurs through the projection of incandescent particles, convective transfer, and radiation. Thermal transfer by radiation constitutes the most frequent and dangerous propagation mechanism, having the capacity to initiate the self-ignition of targets located at considerable distances from the initial fire source.

3. INTEGRATION OF UAV SYSTEMS IN EMERGENCY SITUATIONS

UAV systems designed for firefighting represent evidence of the evolution of technological engineering, distinguished by their capacity to execute critical missions in industrial scenarios where direct human intervention becomes physically impossible [8]. A fire occurring in a production hall or an industrial warehouse typically involves the ignition of massive quantities of synthetic materials and substances with complex chemical properties. This thermal load radically alters fire behavior, generating an operational environment incompatible with human survival.

The dynamics of fires in such enclosed spaces are determined by the volume of available oxygen and the degree of enclosure ventilation. When the combustion process evolves uncontrolled, the onset of critical thermodynamic phenomena becomes inevitable. One of the most critical is the flashover phenomenon, which represents the transition to fully developed fire. It occurs when thermal radiation emitted by the smoke layer accumulated at ceiling level simultaneously heats all combustible materials within the enclosure to their autoignition temperature [9].

Another major risk is the backdraft phenomenon (combustion gas explosion). In well-insulated industrial halls, latent fire rapidly consumes oxygen, generating an atmosphere supersaturated with hot flammable gases. Any action that allows the sudden admission of fresh air (for example, the opening of an access point by a reconnaissance team) triggers a violent explosive ignition manifested outward, making it impossible for intervention forces to enter safely [10].

In addition to these unpredictable thermal phenomena, the industrial environment precludes human intervention due to the extreme toxicity of the atmosphere. The combustion of plastics and chemical agents releases lethal concentrations of hydrogen cyanide (HCN), carbon monoxide (CO), and corrosive compounds. Visibility drops to zero, and the superheated, toxic air can cause severe chemical burns even to personnel equipped with self-contained breathing apparatus.

The second major constraint is the risk of imminent structural collapse. Metal structures, characteristic of industrial halls, lose their load-bearing capacity at temperatures exceeding 500–600°C. The deformation of steel beams under thermal stress exponentially increases the risk of roof collapse. In the presence of these physical and thermodynamic barriers, the use of continuously powered UAV systems becomes a viable alternative, as they are capable of approaching the fire zone and performing effective tactical cooling of structures [11–13].

4. TECHNICAL ARCHITECTURE OF UAV SYSTEMS

UAV systems are designed to fulfill three essential functions in disaster management: aerial surveillance, prevention of fire spread, and active intervention through suppression [14]. This multifunctional approach enables drones to provide an overall view of the incident and to act directly on the fire source.

The architecture of drones is based on a series of interdependent subsystems, each optimized to meet specific mission requirements:

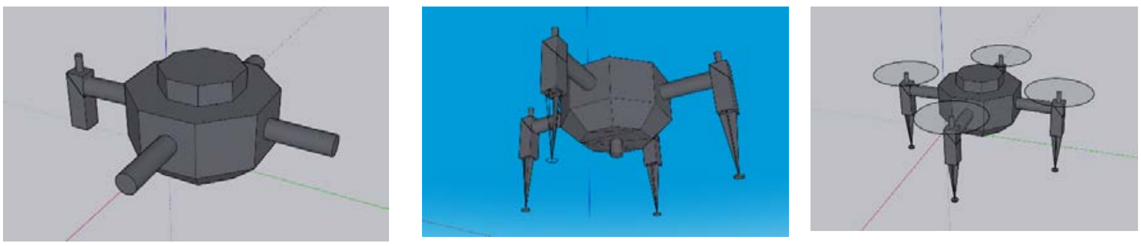
- Propulsion system: Ensures the thrust required for lifting the drone and its payload (including the supply hose), guaranteeing flight stability even in the presence of thermal turbulence generated by fires.
- Control system: Manages flight automation and maintains stability through onboard sensors that process navigation data in real time.
- Sensor system: Utilizes digital cameras and thermal sensors to identify the exact location of the fire source and to monitor its evolution through areas with reduced visibility due to smoke.
- Continuous supply suppression system: Represents the core of the platform's active intervention capability. To eliminate the weight and volume limitations of internal tanks, the aircraft tows a high-pressure hose directly connected to the discharge outlet of a ground-based fire engine. This enables continuous discharge of the extinguishing agent and maximizes the cooling capacity of structures.
- Communication system: Establishes a bidirectional data link between the aircraft and the ground station, allowing the operator to make decisions based on immediate visual evidence [15].

5. CASE STUDY: SIMULATION OF UAV SYSTEM INTERVENTION IN AN INDUSTRIAL ENVIRONMENT

The computational analysis was based on the use of a suite of specialized software solutions. Each application fulfilled a specific function in the transition process from the architectural design of the industrial warehouse to the advanced simulation of fire and smoke propagation [16].

AutoCAD was used to create the (2D) plans of the industrial warehouse. At this stage, the building dimensions and the layout of the production lines were established, in accordance with specific design standards.

SketchUp was employed for the three-dimensional (3D) geometric modeling of UAV systems and robotic arms. This stage was necessary to ensure an accurate representation of the shape and volume occupied by the drones before being imported into the simulation environment (FIG. 1).



(a) (b) (c)

FIG. 1 The 3D geometric modeling process of UAV system

PyroSim (FDS - Fire Dynamics Simulator) constituted the primary computational engine, enabling the integration of geometric elements (FIG. 2) and the simulation of thermochemical reactions through the modeling of combustion product transport and heat transfer within the enclosure.

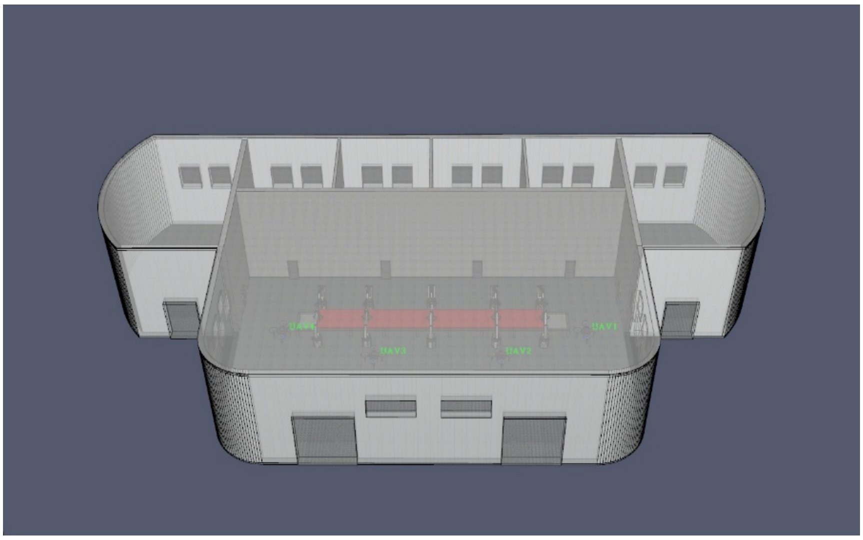


FIG. 2 Illustration of the construction of the industrial warehouse in 3D format

To ensure a realistic and scientifically grounded simulation, the data entered into the PyroSim program were based on technical calculations and real risk scenarios. Thus, the fire dynamics were defined through the heat release rate (HRR) curve, whose evolution over time is illustrated in FIG. 3.

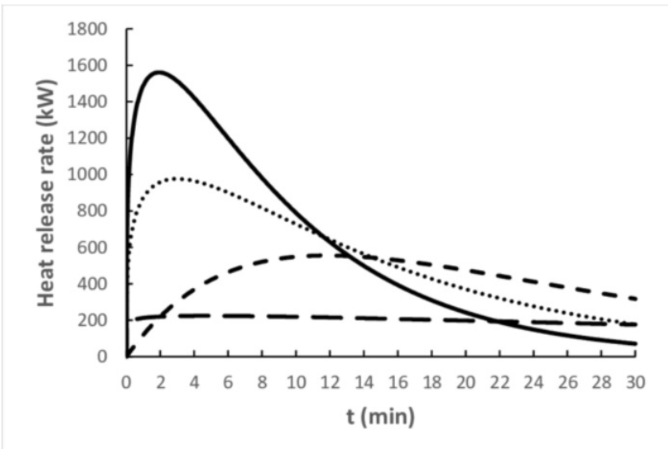


FIG. 3 Heat release rate for hydraulic oil [17]

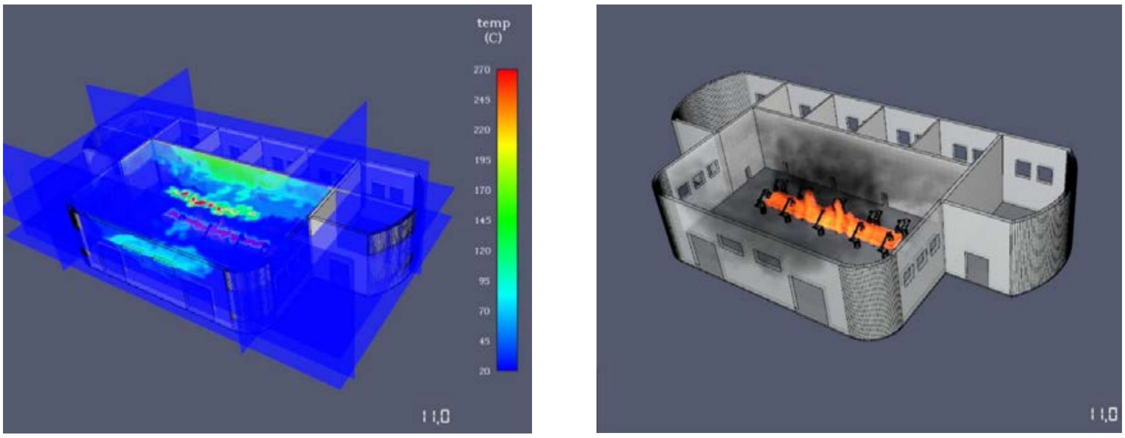
To reproduce the suppression method using UAV systems, water discharge was simulated by attaching discharge nozzles beneath each geometric model of the drones. The configuration of these elements involved the introduction of physical parameters capable of accurately reproducing the properties of a high-pressure water jet.

This experimental design enables the evaluation of tactical efficiency through two comparative scenarios. The first scenario models the free, uncontrolled evolution of the fire source, while the second scenario integrates the suppression action executed simultaneously by four UAV aircraft, maintaining identical initial thermodynamic conditions.

In both cases, the analysis focuses on the spatiotemporal variation of two essential parameters: the temperature field and visibility. These indicators were selected because they represent the fundamental tenability criteria that determine the feasibility and safety of a potential human intervention.

6. ANALYSIS AND INTERPRETATION OF RESULTS

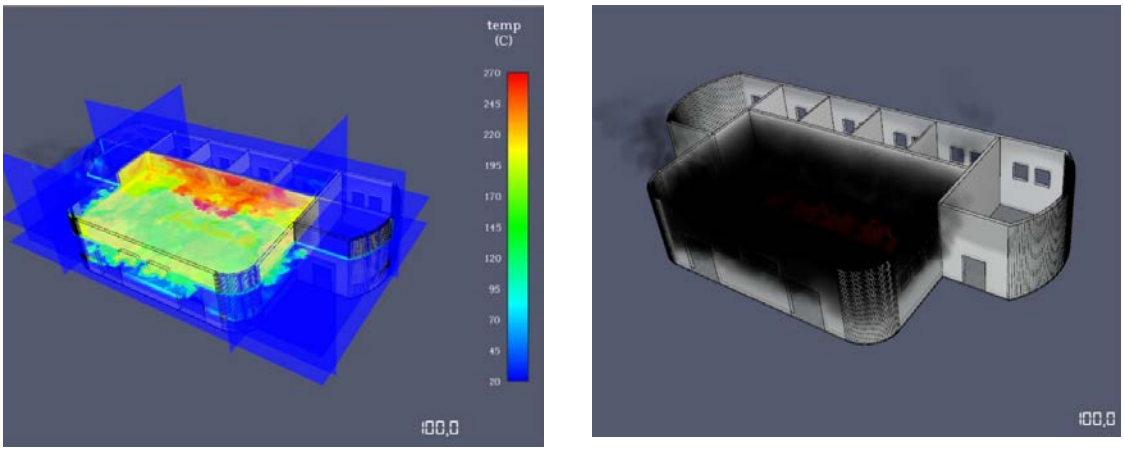
6.1. Analysis of the free-burning fire. The first stage of the computational analysis involves the simulation of fire development in the absence of any active intervention systems. This allows the monitoring of how critical parameters, such as temperature and visibility, evolve naturally in space and time.



(a) (b)

FIG. 4 Evolution of the free-burning fire after 11 seconds

In the initial phase of the free-burning fire simulation (FIG. 4a), the thermal profile highlights a localized development of the combustion process. At the center of the fire source, temperatures reach values between 170 °C and 195 °C. Heat transfer occurs predominantly in the vertical direction, with hot gases subsequently migrating toward the upper extremities of the enclosure, where they reach values of up to 160 °C. In the rest of the warehouse volume, the environment is not yet disturbed, remaining at the reference ambient temperature (20 °C). From the perspective of tenability (FIG. 4b), due to the incipient stage of combustion and the reduced quantity of released particles, the visual field remains completely unaffected at this stage.



(a) (b)

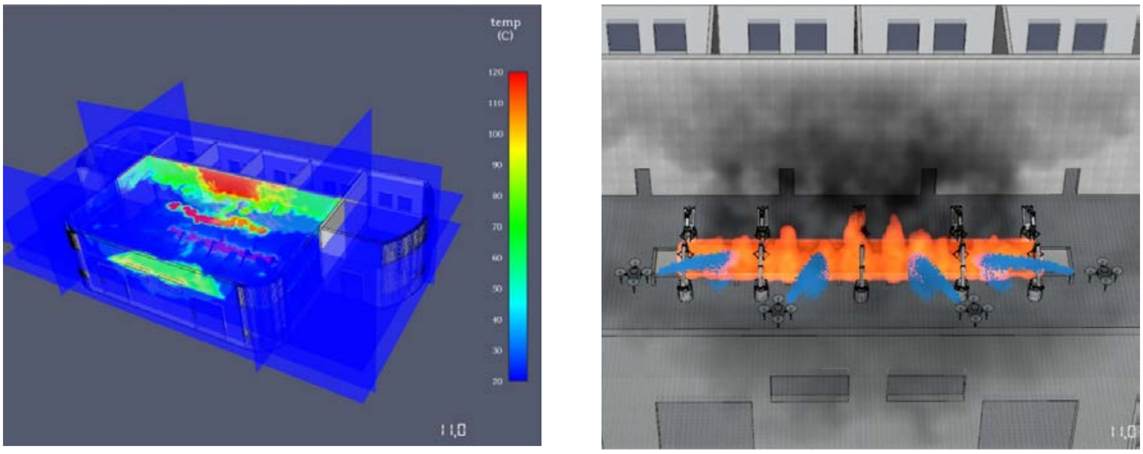
FIG. 5 Evolution of the free-burning fire after 100 seconds

In the final phase of the free-burning fire simulation (FIG. 5a), the thermal profile indicates an advanced development of the combustion process, with temperatures at ceiling level reaching maximum thresholds between 245 °C and 270 °C. The analysis highlights the phenomenon of thermal stratification and the horizontal expansion of the hot gas layer beneath the ceiling, while in the lower areas the temperature varies between 70 °C and 130 °C.

From the perspective of tenability (FIG. 5b), a severe degradation of visibility is observed in most of the enclosure, a phenomenon caused by the accumulation and generalized dispersion of combustion products inside the warehouse.

6.2 Analysis of the fire under the action of UAV systems. The second stage of the computational analysis involves the simulation of fire dynamics under the direct action of four UAV platforms with a suppression role.

This operational scenario examines the impact that drone intervention has on the thermal profile and visibility, evaluating the system's ability to halt temperature increase and to create a stable environment inside the warehouse for the safe access of ground crews.

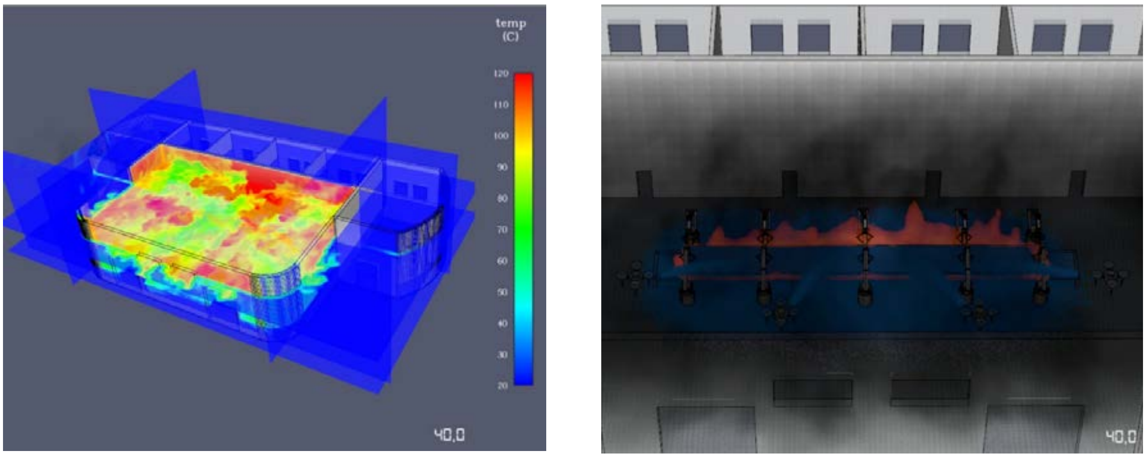


(a) (b)

FIG. 6 Evolution of the fire after 11 seconds under the action of UAV systems

In the initial phase (FIG. 6a) of the UAV systems intervention (triggered at the 10th second of the simulation), the thermal profile indicates a concentration of heat in the upper area of the fire source, however the maximum temperatures are limited to the threshold of 120 °C. Hot gases are retained above the fire source and at the level of the adjacent wall, while the rest of the enclosure maintains the ambient temperature of 20 °C. A spatial expansion of the thermal zone is observed compared to the reference scenario.

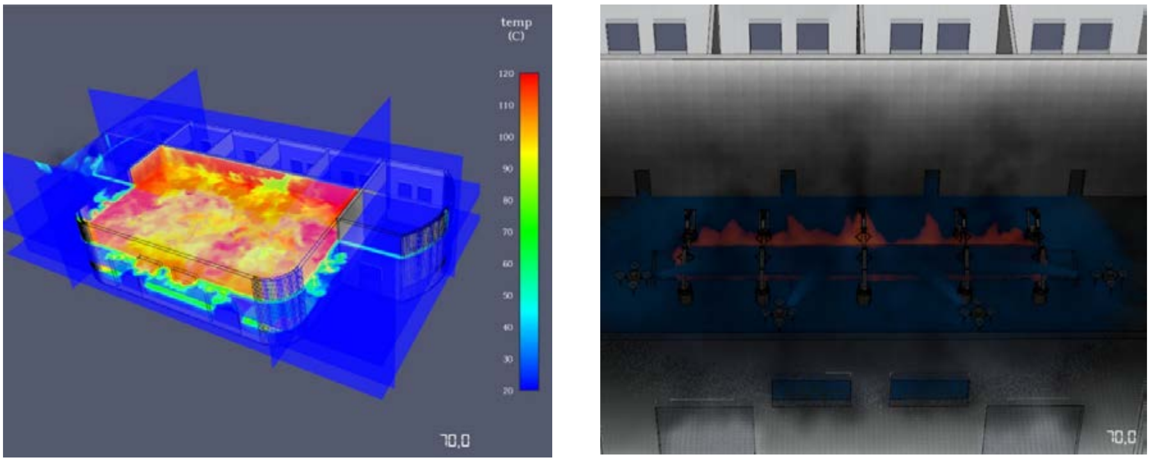
This phenomenon is the direct result of the suppression action (FIG. 6b): upon contact with the fire zone, the water jet vaporizes, generating a massive expansion of steam and a hydrodynamic disturbance of the convective currents. Thus, thermal energy is dissipated and redistributed within a larger volume, but with a significant decrease in peak temperature.



(a) (b)

FIG. 7 Evolution of the fire after 40 seconds under the action of UAV systems

After 40 seconds of simulation (FIG. 7a), the thermal profile highlights an expansion of the hot gas layer at ceiling level, with temperatures maintained around 120 °C. A disturbance of thermal stratification is observed in the area of drone action, where the values indicate local cooling, decreasing within the range of 70 °C – 90 °C. From the perspective of visibility (FIG. 7b), a moderate accumulation of combustion products is recorded in the ceiling area, while the lower level of the warehouse maintains optimal visibility parameters.

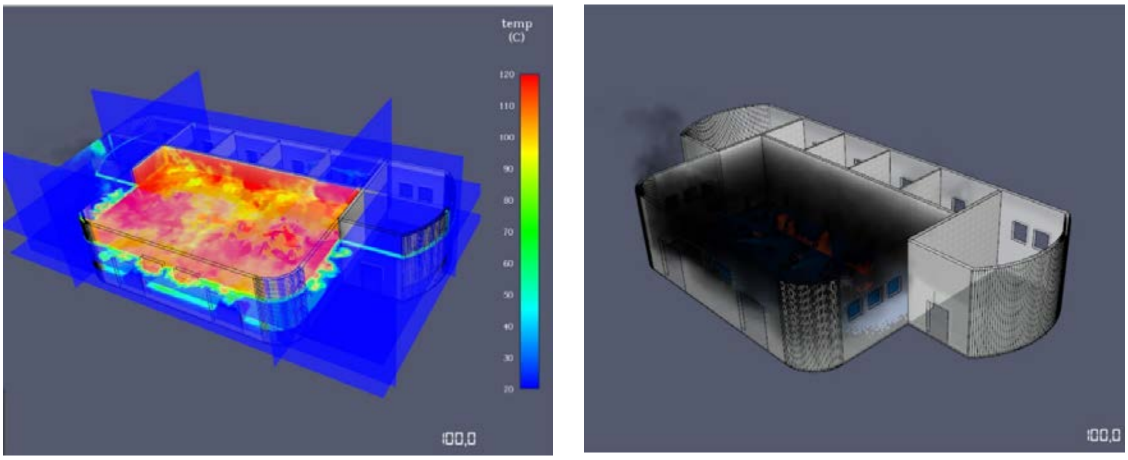


(a) (b)

FIG. 8 Evolution of the fire after 70 seconds under the action of UAV systems

At the moment recorded after 70 seconds from the initiation of the fire (FIG. 8a), the thermal profile indicates a stabilization of maximum temperatures, which remain consistently below the threshold of 120 °C at ceiling level. The expansion of medium-temperature zones (values between 70 °C and 90 °C) confirms the efficiency of the continuous cooling process sustained by the UAV systems on the thermal core.

The simulation dynamics highlight a reduction in combustion intensity and an isolation of the fire zone, its perimeter being saturated with extinguishing agent (FIG. 8b). At the same time, it is observed that part of the hot gases, which now reach residual values of only 60 °C, are evacuated outside the enclosure.



(a) (b)

FIG. 9 Evolution of the fire after 100 seconds under the action of UAV systems

In the final phase of the simulation, the visual representations indicate a uniform thermal distribution across the entire ceiling (FIG. 9a), as well as a significant reduction in the total amount of smoke (FIG. 9b).

The comparative analysis of the two scenarios highlights a major difference in thermal energy management, with the intervention of UAV systems reducing the maximum temperature from 270 °C to approximately 120 °C. While in the first scenario the hot gases generated a compact and hazardous thermal layer beneath the ceiling, the presence of the drones disrupted this dynamic, preventing excessive heat accumulation. Crucially, in the lower half of the warehouse, the maximum temperature was limited to 50 °C. This drastic reduction of the thermal gradient, corroborated by the maintenance of clear visibility at ground level, ensures a tenable environment that allows the safe access of human crews. Thus, the operational effectiveness of UAV systems in limiting fire propagation and protecting the building structure over the analyzed 90 seconds is demonstrated.

7. DETERMINATION OF CRITICAL PARAMETERS FOR THE DESIGN OF THE UAV SYSTEM

The effectiveness of intervention in the studied industrial environment depends on adapting the drone's technical specifications to the thermal and visibility conditions identified in the simulation. Based on the temperature differences and the observed fluid dynamics, the following essential parameters were extracted:

- Thermal resistance and materials: Since the temperature in the operational area has been stabilized at 120 °C, the drone's structure must be made of advanced composites, such as carbon fiber, treated with an outer layer of heat-reflective paint. This configuration ensures the structural integrity of the chassis during prolonged exposure, preventing the robotic arms from deforming under the influence of radiant heat.
- Sensors and navigation (LiDAR technology): Considering the severe decrease in visibility during the advanced phase of the fire, the drone must use thermal imaging cameras and LiDAR (Light Detection and Ranging) detection systems.
- Stability in airflow: Fire dynamics generate high-intensity ascending convective currents. The drone's motors must have sufficient power to maintain a fixed position above the fire source, thus ensuring the stability required to act effectively on the fire zone without being destabilized by thermal turbulence.

- Autonomy and payload: Design specifications must provide for a payload of at least 15–20 kg for transporting the pumping system. This configuration must ensure an operational flight duration that exceeds the critical time of 90 seconds observed in the simulation, allowing both fire suppression and the safe withdrawal of the unit.
- Protection against external factors: Intervention with a high-pressure extinguishing agent creates an environment saturated with vapors and combustion products. Therefore, all electronic components and motors must have a protective barrier that renders the drone completely sealed against fine solid elements (dust) and water-resistant, ensuring operation without short-circuiting during discharge and in the presence of combustion products.

CONCLUSIONS

The present study evaluated the impact of using UAV systems in the management of industrial fires, highlighting the capability of these technologies to compensate for the limitations of human intervention. The intervention of drones demonstrated a high-performance capacity for heat management in enclosed spaces. By discharging water directly onto the fire source, the systems limited the hot gas layer and prevented heat accumulation beneath the ceiling, maintaining the temperature at approximately 120 °C, compared to 270 °C in the case of the free-burning fire. This action preserved an optimal level of visibility in the lower part of the warehouse, where the maximum temperature of 50 °C allows crew access under safe conditions. The use of four drones enabled an optimal approach to the fire source, limiting its spread and demonstrating that robotic systems are an effective option when human intervention is too risky.

Computational modeling proved to be a fundamental tool for establishing the technical requirements of the drones. The reproduction of the free-burning scenario provided a solid database for determining the required level of thermal insulation, the type of sensors capable of operating in dense smoke (such as the LiDAR system), and the power required by the motors to maintain stable flight in hot air currents. Thus, digital analysis enabled the clear definition of design parameters based on physical phenomena, ensuring the development of equipment adapted to the challenging environments of industrial warehouses.

Beyond the virtual testing of equipment, numerical modeling plays an essential role in protecting the safety of intervention personnel. The program’s ability to anticipate the rate at which visibility decreases and the manner in which heat spreads allows the identification of the moments when a fire transitions from a controllable phase to a critical state. These predictions highlight the rapidity with which an industrial environment becomes hazardous for humans (in less than 90 seconds), anticipating the risk of structural collapse or the accumulation of toxic gases. In this way, simulations provide clear arguments for incident commanders to prioritize the use of unmanned systems instead of exposing human crews to risks.

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