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AUTONOMOUS PROTECTION OF INFRASTRUCTURE AGAINST FOREST FIRES

Dissertation within the scope of Master's degree in Mechanical Engineering advised by Professor Doctor José Manuel Baranda Ribeiro and by Professor Doctor Luís Carlos Duarte dos Reis and presented to Mechanical Department from Faculty of Science and Technology of University of Coimbra

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Autonomous Protection of Infrastructure Against Forest Fires

Submitted in Partial Fulfilment of the Requirements for the Degree of Master's in Mechanical Engineering in the speciality of Energy and Environment

Proteção Autónoma de Infraestruturas Contra Incêndios Florestais

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"Research is to see what everybody else has seen, and to think what nobody else has thought."

Albert Szent-Gyorgyi

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Abstract

Reports on the effects of the severe wildfires that happened in Portugal in 2017 highlighted the importance of telecommunication stations in firefighting systems. The failures that occurred in these electronic communication infrastructures due to forest fires caused several types of problems on the emergency networks that created difficulties in alerting the population and interacting with fire stations during firefighting and rescue operations.

To mitigate the weaknesses and critical failures found in these infrastructures located in fire hazard severity zones, the Association for the Development of Industrial Aerodynamics (ADAI) has developed some protection systems. This institution had been developing some systems that coupled with the small telecommunication stations located in fire hazard severity zones would be able to protect and ensure their constant operation in situations of fire in their surroundings.

Thus, this project aims to develop an autonomous system capable of detecting that infrastructure is under fire risk based on the temperature measurement and it is capable of responding by triggering a firefighting mechanism composed of sprinklers and pressurized water tanks with the capacity and pressure necessary to protect the telecommunication stations. The firefighting mechanism is controlled by an Arduino that reads the information from the temperature sensors and activates a solenoid electro valve that spread the firefighting fluid through the sprinklers when the temperature reaches the set-point value. Every time the system is activated, the adjacent area to the infrastructure is wetted, reducing the flame intensity and therefore the temperature of the cabinet keeping operation.

The experimental tests were carried out at Forest Fire Research Laboratory (LEIF), in Lousã, and showed that the developed autonomous protection system proved to be a good solution to protect small infrastructures like telecommunication cabinets.

Keywords Forest Fires, Autonomous System, Telecommunications Station, Prevention, Safety.

Resumo

Os relatórios dos grandes incêndios ocorridos em Portugal em 2017 evidenciaram a importância das estações de telecomunicação nos sistemas de combate a grandes incêndios. As falhas causadas pelos incêndios florestais nas infraestruturas de telecomunicação causaram sérios problemas para a população e para as entidades de proteção civil, impedindo a emissão de alertas à população e a comunicação entre os diversos elementos da proteção civil e emergência médica.

Com o propósito de prevenir as fragilidades do sistema e mitigar as falhas críticas verificadas nas estações de telecomunicações localizadas em zonas de risco de incêndio, a Associação para o Desenvolvimento da Aerodinâmica Industrial (ADAI), tem desenvolvido dispositivos, que acoplados aos armários das estações de telecomunicação, protegem e asseguram o seu constante e correto funcionamento em situações de fogo nas suas imediações.

Neste trabalho foi desenvolvido um sistema autónomo comandado por uma placa de Arduino, que com base na leitura das temperaturas de diversos termopares dispostos nas imediações das estações de telecomunicações, ativa uma electroválvula que permite espalhar água através de aspersores posicionados por cima do armário de telecomunicações. A electroválvula é acionada cada vez que é atingida uma temperatura pré-estabelecida pelo *software*, molhando a zona adjacente à caixa de telecomunicações, reduzindo assim a probabilidade de propagação das chamas e simultaneamente impedindo o sobreaquecimento da caixa de telecomunicações, permitindo manter as suas condições de funcionamento.

Os testes experimentais realizados no Laboratório de Estudos sobre Incêndios Florestais (LEIF), na Lousã. Estes ensaios experimentais demonstraram que o sistema de proteção autónomo desenvolvido provou ser uma boa solução na proteção de pequenas infraestruturas como os armários de telecomunicação.

Palavras-chave: Incêndios florestais, Sistema autónomo, Estação de telecomunicações, Prevenção, Segurança.

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List of Symbols

M_T - Fuel load mass [kg]

C - Specific fuel load [kg/m^2]

m_f - Fuel Moisture Content [%]

A - Fuel bed area [m^2]

T - Temperature [°C]

R - Rate of spread [cm/s]

R_0 - Basic rate of spread [cm/s]

R' - Nondimensional rate of spread []

U - Flow velocity [m/s]

I - Propagation intensity [MW/m]

ΔH_c - Heat value of the fuel [MJ/kg]

Acronyms

LEIF – Forest Fire Research Laboratory

DEM – Department of Mechanical Engineering

FCTUC – Faculty of Sciences and Technology of the University of Coimbra

ROS – Rate of Spread

IR – Infrared spectrum

NI – National Instruments

1. INTRODUCTION

1.1. Climate Change and Forest Fires

The effects of climate change are evident with a growing trend toward increased fire risks, longer and more intense fire seasons that spread more quickly, and traditional firefighting means can’t do much about it (United Nations Environment Programme, 2022).

Every year forest fires affect mainland Portugal causing social, economic, and environmental damage. An example of the destruction caused by the forest fires was 2017’s large fires, which showed that Portugal was not sufficiently prepared to face a natural disaster such as forest fires, with 356 forest fires reported for a total burned area value of 520,515 hectares, as well as more than 100 fatalities in the fires from June to October 2017 (ANACOM, 2017). More countries suffered every year large forest fires such as the USA, Australia, Greece, Italy, France, and Spain. For this reason, it is extremely important to establish a professional structure specialized in fire prevention and extinction in Portugal in cooperation with other countries.

To ensure the safety and well-being of citizens it’s important to ensure all prevention measures and infrastructures to protect the population in case of fires. In this way, the 2017 forest fire reports were made to understand the reasons and Portugal’s fragilities in the protection and control of fires and the changes that should be implemented in the country (Viegas, 2019).

The reports made after the major fires of 2017 determined that many telecommunications stations, poles, and copper and fibre optic cables were destroyed, thus contributing to the failures of the communication system of the firefighting and emergency help services, being that "the complexity of the situation experienced exceeded the capacity of coordination of means, which was aggravated by communication failures" (Viegas, 2019). Nowadays, data communication and the network are omnipresent in all activities, requiring a permanently functional communication network with high-quality infrastructure. Changes in climate and climate extremes lead to huge impacts, as recent disasters have proved, therefore ensuring a communication network system that is resistant to weather change is crucial.

1.2. Motivations

In a period where climate change is an increasing reality, there is a greater chance of natural disasters of higher intensity happening. Considering the 2017 forest fires and the weakness of the specialized professional structure for the prevention and extinguishing of fires in Portugal, other failures that occurred contributed to the difficulties felt in fighting fires and in the response of the emergency operational services to help the population. One of the main reasons for such failures was the damage to the telecommunication stations, causing the communication network to fail.

The major fires of 2017 played a key role in raising awareness about the importance that telecommunication stations have in coordinating firefighting services and the population's safety. In this context, the motivation for this work was to develop a protection mechanism for telecommunication stations at risk of fire capable to maintain their operation during forest fire disasters.

In this way, the scope is to design an active protection system for telecommunication stations that would be activated autonomously, and hands-free. So, in the near future, these stations will have fewer chances of being damaged and causing communication failures in dangerous situations and conditions.

This work was part of the investigation of the Projects FCT, FIRESTORM (PCIF/GFC/0109/2017), MCFIRE (PCIF/MPG/0108/2017), SafeFire (PCIF/SSO/0163/2019) and SMOKESTORM (PCIF/MPG/0147/2019). In these projects, the fire behaviour, the protection and safety systems, and the moisture content of forest fuels are analysed, taking into account the ongoing climate changes that create more frequent conditions for the occurrence of droughts and heat waves that make it easier the incidence of Extreme Wildfire Events (EWE).

1.3. Objectives

The present work focuses on the development of an autonomous mechanism that reacts to temperature increases triggering a water system that allows to stop or reduce fire near telecommunication station cabinets protecting it in fire hazard scenarios. This mechanism was designed to be placed together with the cabinet, with the sprinklers placed on top and the sensors in the surroundings to detect the fire as soon as possible.

Firstly, the work comprises the development of an electronic system (Arduino) capable of activating a solenoid valve that activates the propagation of water by the sprinklers providing the humidification of the area around the cabinet when the temperature near the box reaches the set point.

Secondly, to test the designed system for different types of flames and water spread scenarios to assess the system response and ability to prevent damage to the telecommunications cabinet.

1.4. State of the Art on Fire Protection of Telecommunication Cabinets

The work to be developed arises as a continuation of previous studies by Barge (2019) and Brinca (2020) who used an aluminium-coated fibreglass blanket to protect a telecommunications cabinet from fire, and the studies carried out by Monteiro (2021), who used rigid panels applied to a cabinet identical to telecommunications stations to protect against fire (Figure 1.1).

a) Aluminium-coated fibreglass blanket (Brinca, 2020)

b) Rigid panels (Monteiro, 2021)

Figure 1.1 Two experimental setups to protect the communication cabinet.

These studies proved to be interesting and a good solution to increase the protection of the telecommunication cabinets, especially the protection consisting of rigid panels, which proved to be highly effective to reduce the thermal impact felt by the cabinet. In a situation of fire exposure with the protection applied, the temperatures on the outer surface and especially inside the cabinet do not increase as sharply as when the cabinet is unprotected (Monteiro, 2021).

The two studies carried out using an aluminium-coated fibreglass blanket also proved to be a solution capable of reducing the temperatures inside telecommunication cabinets and the correct functioning of the radios. In the study carried out by Brinca (2020), an in-depth study was performed using numerical simulation, which proved that this passive protection reduces the temperatures measured in telecommunication cabinets in fire situations compared to when the protection was not in use. However, there were also some limitations caused by the protective blanket, for example in terms of cabinet ventilation.

In this work, a different and more practical solution was designed, through a mechanism somewhat similar to the systems currently existing in large commercial kitchens to protect them against fire. These systems were designed to protect restaurants and their occupants but are also starting to be applied to other uses such as student housing, barbecue grills, apartment buildings, and other applications.

This autonomous system works by having nozzles displayed above the flames and when detecting a fire, they automatically discharge the wet chemicals covering the fire and starving it of oxygen. As we already know a fire lacking oxygen loses the fuel that is needed to proliferate so this way it is possible to suppress a fire. For each application different chemicals are required to do fire suppression successfully, so the fire won’t have oxygen to burn (Fire Pros, 2021). These systems, which are designed to prevent fires, typically only react once a wildfire has broken out. On the other hand, preventative oxygen reduction systems work before a fire started. These systems can protect sensitive areas from fire and toxic smoke gases by oxygen reduction techniques that are based on cutting off the energy supply needed to support the ignition process and fire propagation.

Nitrogen is an example of a non-toxic gas that works as an oxygen reduction system in the air, can provide fire protection and minimize the risk of accidental exposure to certain areas (National Fire Protection Association, 2019). Another example is carbon dioxide, the most widely used gas extinguishing agent. It is about twice as effective as nitrogen. Both are commonly used to prevent fire hazards in certain types of electrical equipment, flammable liquids and combustibles.

Comparing these oxygen reduction systems techniques with the original method of using water, it was observed that water absorbs more heat. This means that it is necessary much more liquid nitrogen to put out the same fire (Wildfire Today, 2020). Another negative impact of using nitrogen to stop a fire is that after the initial flame goes out, the nitrogen evaporates very quickly. If you extinguish part of a forest with it, the flames can spread back to that area minutes later. If you extinguish part of a forest with water, it will remain liquid, soak the wood, and make it much harder for the fire to come back (National Fire Protection Association, 2019). In addition to being much easier to come by, and easier to transport and handle, water is much more effective.

1.5. Structure of the Dissertation

This dissertation is divided into five chapters. Each chapter is composed of sections and subsections, considering the main aspects of the work. The sections and subsections of each chapter are arranged to convey ideas to the reader in the most appropriate order to better understand the overall work.

In Chapter 1 it is present an overview of the work.

Chapter 2 introduces literature research on the basics of fire dynamics, extinguishing agents and the Arduino platform.

Chapter 3 describes the methodology adopted for experimental setup and treatment of results.

Chapter 4 the results are presented, and the most relevant capabilities and system performance are discussed.

Chapter 5 is the conclusions and study proposals to continue this work.

2. FUNDAMENTALS OF IMPLEMENTATION RESEARCH

This study focuses on designing a system that can protect telecommunications cabinets located in fire hazard zones without the need for human presence, protecting firefighters from situations where extreme conditions put in danger their safety.

In order to develop this project, it’s extremely important to understand fire behaviour in a better way, making it possible to predict the direction of the fire, the rate of spread and also know when the best time is to activate the water mechanism to fight it.

2.1. Fire Dynamics

Fire dynamics is the study area that encompasses how fires start, spread, develop, and are extinguished, this analysis is fundamental because it can provide a firefighter with the means to understand how a fire will grow and spread and what is best to control that growth (Madrzykowski, 2013).

To be able to design a system capable of detecting and protecting telecommunication stations from fire efficiently it is fundamental to know what fire behaviours are. A combustion can be described as a chemical reaction that happens in the presence of a fuel and an oxidant, to occur this chemical reaction is necessary an ignition that can happen through an external heat source and that provides the necessary energy to trigger the chemical reaction between the fuel and the oxidising agent, originating fire. Another important factor to consider is flammability, which is the amount of energy required to produce the ignition, that is the ease with which ignition occurs (Viegas, 2006).

When a fuel particle is exposed to a heat source, first loses the water that it contains and then releases volatile flammable components that undergo a combustion reaction. If the reaction occurs on the surface of the fuel, with no release of volatiles, flameless combustion occurs. If the reaction occurs in the gaseous state, a flame is formed, which often occurs in a forest fire with surface propagation. Understanding fire behaviour is fundamental in forest fire management as it determines the strategies and measures to be adopted (Viegas, 2006).

According to most studies, wildfire development has three principal factors that build the known “Wildfire Triangle” (Byram, 1959), as shown in Figure 2.1. The three pillars of this triangle are fuel, weather, and topography.

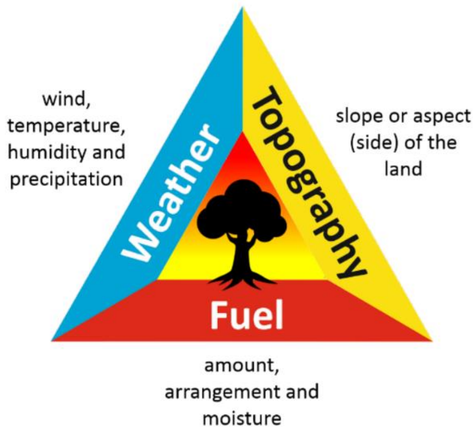

Figure 2.1 Wildfire Triangle (Kern et al., 2020).

These three main factors were deduced from the original “Fire Triangle” which shows the three important preconditions for starting a fire, which are fuel, oxygen, and heat. All these three must be present for a fire to ignite, if one of these main factors is not available, it is possible to control a fire, however, this is not as easy to do as it seems.

Regarding fuel, a fuel's flammability is determined by its composition, which includes among other properties, the moisture content, chemical composition, and density. The most significant consideration is the moisture content. These fuels' moisture levels and distribution determine how quickly and intensely a fire can spread. Because the heat of the fire must first evaporate the moisture, the high moisture content will slow down the combustion process.

The chemical composition of the fuel, in addition to moisture, influences how fast it burns. Some plants, shrubs, and trees possess oils or resins that aid combustion, allowing them to burn more easily, quickly, and powerfully than others that do not. Finally, flammability is influenced by the density of the fuel. Fuel particles that are too close together will ignite each other with ease.

Wind, weather, temperature, and humidity are all factors that influence how fire behaves. All these aspects are part of the weather factor.

One of the most crucial components is wind, which can provide a new supply of oxygen to the fire while also pushing it toward a new fuel source. The susceptibility of a fuel to ignite is influenced by its temperature. Fuels ignite more quickly at high temperatures than at low temperatures. The last important one is humidity, or the amount of water vapour in the air, which has an impact on a fuel's moisture content. Fuels become dry at low humidity levels and, as a result, catch fire more easily and burn faster than when humidity levels are high. It is common to assume a critical period when exists the following combined factors: wing velocity above 30 km/h, air humidity below 30% and fuel humidity below 6% (Torrinha and Gonçalves, 2013).

The term "topography" refers to the shape of a piece of land. The fire spread can be aided or hampered by several topographical factors. Aside from the land's shape, height, slope, and aspect must all be considered.

In terms of weather conditions, as said previously, wind behaviour is the most critical for forest fire propagation. The wind's behaviour is highly unpredictable, its speed may differ for locations adjacent to one another, and its direction may change rapidly, making it difficult to characterize and anticipate its behaviour. Because the wind velocity and direction may fluctuate for different areas of the same fire, and the fire also creates its convective winds, it is difficult to anticipate the behaviour of a forest fire that spans for kilometres. This way according to Viegas (2006) the passage of time has a significant impact on fire behaviour, this aspect is inherently unstable once the previously mentioned characteristics are considered.

As a result, Viegas (2006) suggests a new idea for influencing fire behaviour, renaming the "Wildfire Triangle" to "Wildfire Square" (Figure 2.2).

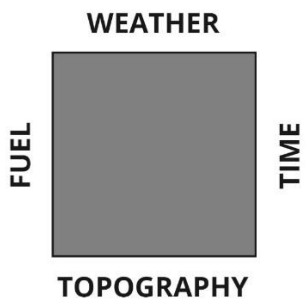

Figure 2.2 Wildfire Square (adapted from Viegas, 2006).

Once the fire has been ignited it is important to understand how the heat is transferred. Heat transfer happens whenever there are elements of one or more systems with a variety of temperatures, this can be done in three different ways, conduction, convection, and radiation. In wildfires, conduction can be ignored because it represents a small percentage of heat transfer compared to the other two ways, which have much higher heat transfer values in vegetation.

This way, the most important heat transmission modes in a forest fire are convection and radiation because they take very high numbers, especially the heat released through radiation which is the energy emitted in the form of electromagnetic waves, whereas in convection the hot gases from combustion come together with the heated ambient air and through convection currents heat the combustibles (Brinca, 2020).

2.2. Active Protection and Passive Protection

There are two types of fire protection systems: active and passive.

Active fire protection systems are equipment and systems that are designed to combat fires and evacuate people, they help to contain, suppress, or extinguish a fire that has already started. Fire extinguishers, automatic showers, fire alarm systems, illumination, and emergency exits are among the active protection systems.

Passive fire protection systems are solutions that are installed in structures to provide fire resistance for a longer length of time, giving structures and people more protection. Passive fire protection systems use fire-resistant walls, floors, and doors to provide people enough time to escape a burning structure. Intumescent coatings, mortars, fire-resistant panels, and fire-resistant fibrous blankets are also among the passive protection solutions that stand out (MAPFRE, 2022).

In this way, the previous studies, described in chapter 1.4, which aimed to develop protection systems for telecommunication stations are integrated into passive fire protection, while this project is focused on active fire protection systems.

2.3. Telecommunication Stations

Telecommunications stations are made up of several devices that work together to create a system that allows people to communicate over the radio.

A transceiver box with radios (cabinet), a tower with antennas, and a transmission line are the three essential components of these telecommunication stations (Figure 2.3). The transceiver is a device that combines an emitter and a receiver and is responsible for signal processing as a result. Electromagnetic energy can be converted to radiated energy or vice-versa using antennas. Finally, the transmission line connects the transceiver to the antennas, allowing the signal to travel between them.

Figure 2.3 Telecommunication stations.

After the 2017 fires, ANACOM issued a set of requirements aimed at protecting and extending the useful life of this equipment, emphasizing the need for proper communications station operation for the management of warfare and the survival of the population. As a result, it became mandatory to create a paved area surrounding the station with an adequate minimum width (1 to 2 meters), cut the tops of trees and bushes within a five-meter radius of the station, clean the land around the station to establish a combustible material management strip (50 meters) and thus become less susceptible to being affected by a fire, clean the interior space of the fence, and promote the replacement of the fence (Figure 2.4).

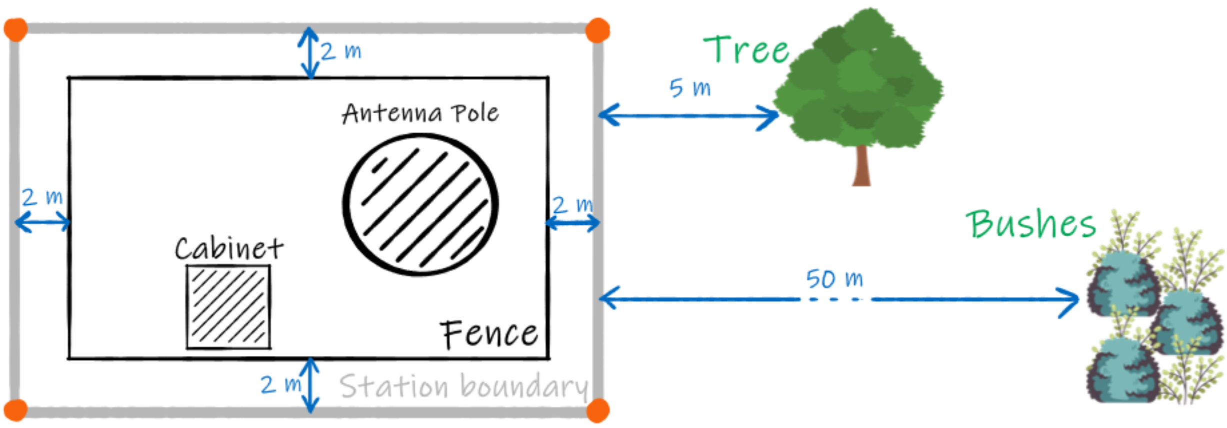

Figure 2.4 Measures associated with telecommunications stations (Adapted from ANACOM 2017).

2.4. Autonomous System

An automatic system that can detect and extinguish, or contain, a fire without the need for human intervention is known as an autonomous fire suppression system. These systems have a means of detection, activation and actuation.

Fully automatic fire suppression systems eliminate the need for a person to detect and extinguish a fire being exposed to flames. The system detects the heat increase because of the approaching fire within seconds of its occurrence and triggers the system that delivers the extinguishing compounds directly into the centre of the fire or to the surroundings of what is to be protected.

These systems have built-in components, like temperature sensors, that will identify fires as soon as possible. The temperatures that increase due to the presence of fire will be detected as soon as possible and the sprinkler system will then release the water, allowing the fire to be put down before it spreads. Since it is initiated in response to the presence of fire, this type of fire suppression system can be termed an 'active' fire protection device.

2.4.1. Extinguish Agent

Sprinkler systems and fire suppression systems can control, extinguish flames and activate when heat or smoke is detected. However, because water can be ineffectual in certain types of flames, it is not the best option to use conventional water sprinkler systems in certain applications. An example of this is a facility that uses combustible gas or oil, using water as a firefighting agent would not be successful. For this reason, in this work, the system that will be used is called the water mist suppression system because this system aims to protect a telecommunication station in an area where the application of conventional water sprinklers would not have the desired effect. After all, it would require the application of water in large quantities that would be difficult to obtain in a forest area.

Initially, the idea of using a fire suppression system in which a chemical compound was used to create an oxygen reduction system was considered. However, this was discarded since this research was aimed toward an external application so it would not be the best solution to place some types of suppression systems when environmental factors like the wind also must be considered.

There are a variety of fire suppression systems on the market, each designed to protect a specific application. In this work, it was chosen to use a water mist fire suppression system because it is a highly effective extinguishing system that generates fine water droplets using water and air. To contain and extinguish a fire, these water droplets generate a mist that covers a vast surface area and when compared to typical sprinklers, utilizes less water per discharge and as a result, has the advantage of large damages and losses being avoided.

The best example of the influence of environmental conditions in fire suppression systems is the wind factor which when it's too strong can make the oxygen scavenging system impossible to work properly, not doing well in the main mission of suppressing or containing the flames of a fire. Unlike these oxygen reduction systems, the low-pressure water mist system effectively extinguishes a fire in seconds and can be highly effective even when there is little wind and that's why it was chosen to be used in this application.

Another aspect that was important to take into account is how the fire extinguishing agent is stored.

To store the fire extinguishing agent firstly was thought of pressurised beer barrels to be used because they have more storage capacity than a classic fire extinguisher and greater heat resistance. However, through this method, it was found that there was the problem of the output pressure being too low for the desired application is necessary for a compressed air bottle to get a higher pressure. For this reason, it was thought to use water extinguishers that guaranteed a higher water output pressure without the need for a complementary element to reach these pressures.

The water extinguisher and the beer barrels that have been studied for the storage of the extinguishing agent are shown in the following figure.

Figure 2.5 Fire extinguishers and metallic barrels were studied for the storage of the extinguishing agent.

2.4.2. Arduino

Arduino is an open-source electronics platform that is easy to use with simple hardware and software. The Arduino board can take inputs from temperature sensors and convert them into outputs such as motor triggers. You can tell the device what to do by giving a series of instructions, by code, to the microcontroller on the board. To achieve this, Arduino assembling (based on wiring), and Arduino programming software called IDE (Integrated Development Environment) are run on the computer and used to create computer code and upload it to the Arduino board.

The Arduino platform is gaining popularity among electrical device beginners. Unlike most previous programmable boards, Arduino does not require separate hardware to load new code onto the board. All you need is a USB cable. In addition, the Arduino IDE facilitates programming by using a simplified form of C++.

In this situation as a complement to the Arduino board, it will be necessary to use modules for the temperature sensors. This module's objective is to convert the temperature read by the K-type thermocouples into Arduino language, allowing the software to detect at what temperature the thermocouples are. For the type K thermocouples used in this mechanism, it was chosen the MAX6675 module. Due to the analogue to digital converter and SPI communication, it's possible to read the temperature values accurately through the Arduino.

Another important element for this autonomous system is the relatively low voltage relays that can easily control high power circuits. The relay uses the 5V output from the Arduino pin to power the electromagnet, which closes the internal physical switch to turn the high-power circuit on or off. This element is important in this case to control the solenoid valve that will allow to open or close the valve that allows the extinguishing agent to exit, which in this case is the water mist.

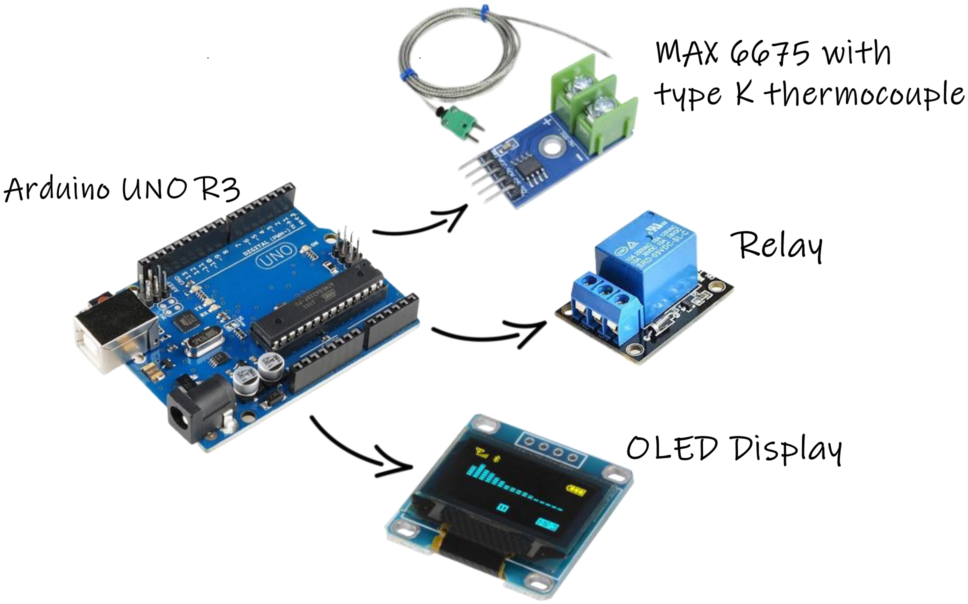

Figure 2.6 Main components of the autonomous system.

3. EXPERIMENTAL METHODOLOGY

This work was divided into two steps with the main goal of protecting telecommunications cabinets and ensuring their correct operation in extreme situations. The first step consisted of the research study on previous works and technologies about fire protection of critical units and the development of an autonomous system to extinguish fire centred on a sprinkler mechanism. Afterwards, experimental tests were carried out in the LEIF facilities in Lousã to understand experimentally the performance of the designed system to extinguish the fire around the cabinet. This chapter describes the experimental setup, the measurement systems and the methodology adopted to process the results.

3.1. Triggering System

The first step in designing the experimental setup was to understand the capabilities of commercial autonomous systems that existed on the market. Based on this analysis was decided to choose the Arduino because it's a good kit for beginners, which facilities the hardware and software interaction with a microcontroller chip in a sort of plug and play.

After this, it was necessary to make and optimize the connections between the controller and the solenoid valve selected for pressurised water release. This aspect turned out to be a difficulty because the Arduino could only transmit signals of 5 V while the electro valve needed at least 24 V to activate. To solve this problem, was necessary a relay with a 24 V power supply to make this conversion so that the signals emitted by the Arduino were received and consequently realized by the electro valve.

Another component required for the operation of this mechanism was the MAX6675 module that allows the reading of thermocouple temperatures. These modules process the thermocouple record and transmit the data through a serial interface. This allows the signal from a type K thermocouple to be digitised. Data is output in 12-bit resolution, compatible with SPI, a read-only format. This converter resolves temperatures to 0.25°C and allows readings up to +1024°C. As a complement, an OLED display was installed to be able to see in real-time which temperatures were measured by the thermocouples, allowing us to see the temperatures in the four different places. Figure 3.1 shows the triggering system.

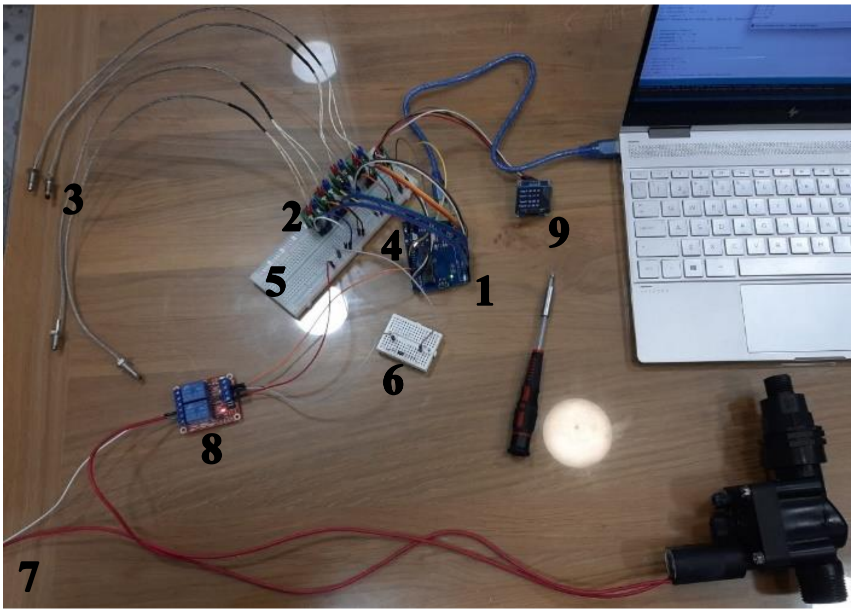

Figure 3.1 Triggering System.

The following components were needed for this triggering system:

1 - Arduino UNO with USB Wire,

2 - Four Max6675 modules,

3 - Four thermocouple's type-K,

4 - Wire jumper kit,

5 - Two breadboards,

6 - Silicon rectifier,

7 - Power supply 24V,

8 - Relay,

9 - OLED Display.

To read the temperatures of the 4 thermocouples and activate or deactivate the solenoid valve according to the temperature read by the thermocouples and its comparison with a set-point, a C++ program was developed. This code was programmed so that every second all 4 temperatures were read and the signal to activate or deactivate the solenoid valve as compared to the set-point to allow or not allow the water to flow out – if one of the thermocouple temperatures reached the set-point the solenoid valve was activated when the temperature of all thermocouples was below to the set-point, the solenoid valve was deactivated. The temperature set in the tests for this set-point was 50ºC.

3.2. Location of the Array of Sprinklers

A set of six sprinklers (three high pressure pesticide misting sprayers with PLd5 nozzles on each arm connected with a T device) were placed in the front area at the top of the telecommunications cabinet (Figure 3.2). The sprinklers were connected to a hydraulic pipe, which had a solenoid valve controlled by the Arduino as a function of the thermocouple temperatures and their comparison with the set-point temperature.

Figure 3.2 Position of the sprinklers at the top of the telecommunications cabinet.

The sprinkler's location was set assuming that the fire propagation is in one direction only. For the experimental tests, the sprinklers were placed on the front of the cabinet, in the direction of the fire because this would be the only part of the cabinet subjected to high temperatures. The sprinklers may have to be placed on other sides depending on the field conditions in a real situation.

3.3. Experimental Tests

To understand the level of protection achieved with this autonomous active protection system some experimental tests were conducted to simulate on a laboratory scale a real wildfire.

The cabinet was exposed to fire for different wind velocities (1 and 2 m/s and zero) to evaluate the performance of the active protection system made of six water mist sprinklers. For all experimental tests a water pressure equal to 3 bar was used.

Table 3.1 shows the most relevant parameters set for each test. At the beginning of each test, laboratory temperature and humidity were registered. The test started when the fuel ignited through a wool line soaked in a mixture of gasoline and diesel. The test ended as soon as it became clear that the fire had been partially extinguished, or the fuel consumed.

The first experimental test (*Test 0*) was the only test that was done without the activation of the sprinkler mechanism, being a reference test.

Table 3.1 Parameters set in the experimental tests.

Tests	Wind tunnel velocity, U (m/s)	Laboratory air temperature (°C)	Laboratory air humidity (%)	Fuel moisture content, m_f (%)	Sprinkler angle to vertical reference (°)	Fan blinds
Test 0	0	20	55	16.7	45	Close
Test 1	0	19.7	54	15.2	45	Close
Test 2	0	18.9	54	14.5	45	Open
Test 3	1	19.6	56	16.8	45	Open
Test 4	2	20.2	50	14.3	45	Open
Test 5	1	19.2	52	13.5	0	Open
Test 6	1	18	54	17.6	90	Open

Figure 3.3 shows the experimental setup used for the experimental tests, view from above.

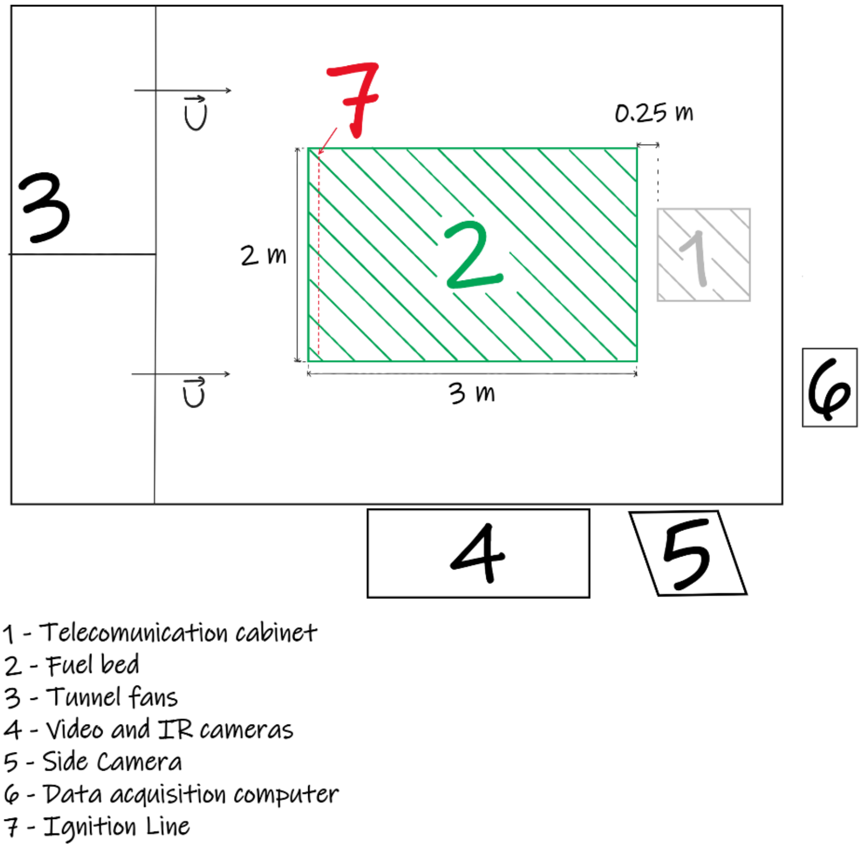

Figure 3.3 The layout of the cabinet, fuel bed and record equipment in the combustion tunnel 3.

The LEIF Combustion Tunnel 3 was used in this study for the experimental tests. The tunnel is equipped with two 35 kW axial fans that can produce a flow rate of up to 8 m/s. The tunnel has 6 meters in width and two side walls, each 8 meters in length and 2 meters high (one of these walls is made of transparent glass, allowing three separate fire viewpoints).

To record the images of fire propagation and extinguishment during the experimental tests carried out 3 cameras were used: 2 digital video cameras (SONY FDR-AX53 and HXR-NX30E) and 1 infrared camera (FLIR SC660). Two of the cameras (infrared and a digital video camera) were placed at the lifting platform, 5 metres above the ground, to measure the rate of spread, and the other video camera was placed at ground level to collect information about the height of the flames.

Type K temperature sensors and a flowmeter were used to record the temperature and radiation of the flames.

The figure below shows the LEIF Combustion Tunnel 3 with all the necessary equipment to carry out the experimental tests.

Figure 3.4 Equipment setup in the experimental tests.

For the placement of the four thermocouples to activate the triggering system, two thermocouples were placed on the front of the cabinet; a third one was placed 0.7 metres ahead of the front of the cabinet, and a last one inside of the cabinet (Figure 3.5). These positions were considered critical to control the temperature of the cabinet and consequently activate or deactivate the solenoid valve. It is also shown in Figure 3.6, the OLED display used in the trigger system to see what temperatures are being read by the temperature sensors every second by the Arduino.

The temperatures shown on the OLED screen are out of order and so below is the arrangement of thermocouples from the bottom to the top of the telecom cabinet and the corresponding temperature read in the triggering system and shown on the OLED screen:

Thermocouple 1 was placed 0.7 metres in front of the cabinet (*Temp2* on the OLED display).

Thermocouple 2 was placed inside of the cabinet (*Temp3* on the OLED display).

Thermocouple 3 was located on the front outer surface of the guard at approximately 0.5 metres from the ground (*Temp4* on the OLED display).

Thermocouple 4 was placed on the outer surface of the cabinet next to the flowmeter, 0.75 metres above the ground (*Temp1* on the OLED display).

Figure 3.5 Triggering system thermocouples location.

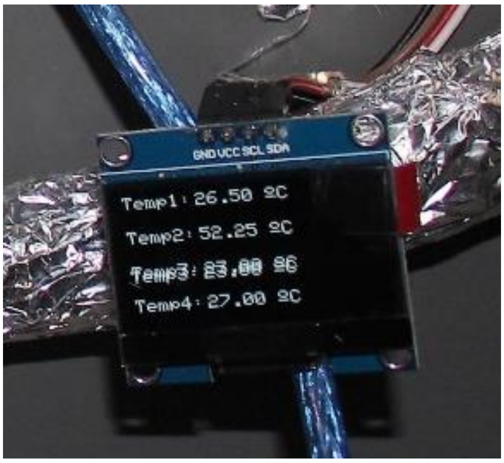

Figure 3.6 OLED display used in the triggering system.

3.3.1. Fuel Load

The fuel used to perform the experiments and simulate a real situation was shrubs. For all experiments was fixed a fuel bed area of 2x3 m.

The total fuel used was calculated as a function of the fuel moisture content and the fuel load. As the amount of moisture content of fuel depends on the time of the day, air humidity and temperature, to maintain the same amount of water in the fuel load the amount of cellulose was varied. To accomplish so, it was first determined the percentage of humidity in the dry base, and then use the following equation to calculate the total fuel for the wet base:

$$M_T = C \times \left(1 + \frac{m_f}{100 - m_f}\right) \times A \qquad (3.1)$$

Where M_T [kg] is the total fuel to be used in experimental test, C [kg/m^2] is the specific fuel load where a value of 1.5 kg/m^2 for all tests, m_f [%] is the fuel moisture content recorded in the analyser (*AND ML-50*, with resolution of 0.1 and Max=51g) and A [m^2] is the fuel bed area.

3.3.2. Ignition

To start the ignition was used cotton yarn soaked in a mixture of gasoline and diesel and placed close to the fan, perpendicular to the flow velocity and fire spread direction, across the width of the bed edge. The result is a linear ignition that produces a more realistic fire, makes it easy to start all the experiments in the same way and makes sure there is no difference in the fire dynamics.

3.3.3. Sprinklers

The purpose of the sprinklers was to generate a mist of small particles of water sufficient to weaken combustion, due to the consumption of heat to evaporate the water, reducing the rate of production of volatile compounds, and consequently reducing the size of the flames and their propagation. Unlike conventional sprinklers that produce larger water particles that fall off without entering the combustion, the small particles of water characteristic of a mist can enter the combustion. Figure 3.7 shows the effect of water mist on fire propagation. These sprinklers have the particularity of being easily found on the common market for agricultural spraying systems.

Figure 3.7 Water Mist Extinguish process.

3.4. Data processing methodology

The main results to analyse were the rate of spread, flame intensity, temperatures reached and the heat flux. For this analysis, each experimental video record was converted to frames to allow the analysis of the progression and height of the flames as a function of time. For each of the tests, depending on the duration, the video record was framed so that there would be around 20 frames per video to allow a higher resolution on the analysis of the influence of the wind speed on the fire front propagation. Three different values for wind speed were tested: 0, 1 and 2 m/s.

To achieve better results a comparison was made between the results of experiments 1, 2, 3 and 4 to understand how windspeed affects the rate of spread, fireline intensity, flame height, and temperatures, and heat flux (Table 3.1 shows the different settings for each experimental test). The study was also carried out to see if there was any advantage to placing the sprinklers at an angle of 0 degrees or 90 degrees, to achieve a greater range of results. Figure 3.8 demonstrates the three positions in which the sprinklers were placed.

a) b) c)

Figure 3.8 Sprinkler inclination at a) 45° (test 3), b) 0° (test 5) and c) 90° (test 6).

3.4.1. Rate of Spread

To perform the calculations of the ROS, the videos captured by the infrared (IR) camera in the lifting platform were, together with the Fire ROS Calculator software (Abouali, 2019), transformed into a set of frames and consequently those frames were used to calculate the rate of spread, for a range of temperatures from 0 °C to 550 °C, throughout all the experimental tests. An example of the frame records used for this analysis is shown in Figure 3.9.

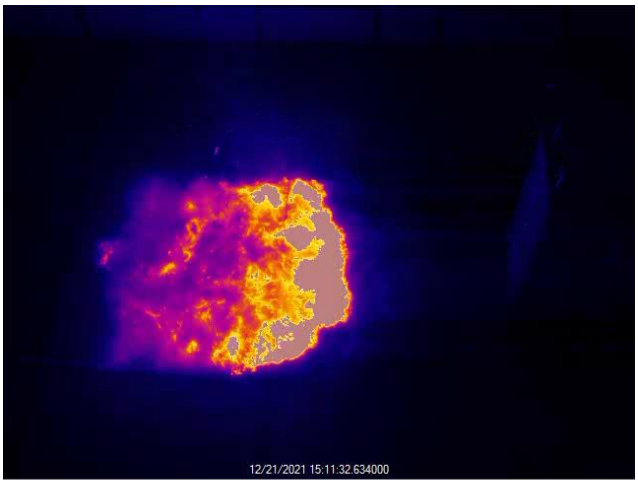

Figure 3.9 Example of an image of the IR camera (test 6).

According to Viegas & Neto (1991), dimensionless parameters are used to reduce variability in the fuel bed qualities. In this way, the rate of spread (R) will be determined using the basic rate of spread (R_0) in its dimensionless form (R'). The basic rate of spread value (R_0) corresponds to the rate of spread achieved in the simplest test possible, in a horizontal bed with a linear flame front, bed width well above the flame height and no wind.

The first experimental trial was picked as a reference test because it meets all the criteria, and after averaging the velocities in that test, we get a result of R_0 of 0.0046 m/s.

The nondimensional parameter of the propagation is calculated using the following equation:

$$R' = \frac{R}{R_0} \tag{3.2}$$

The flame intensity, I, [MW/m]) is calculated using the following equation:

$$I = R \times \Delta H_c \times C \tag{3.3}$$

Where, R [m/s] is the rate of spread, ΔH_c [MJ/kg] is the low heat value of the fuel and assumes the value of 20 MJ/kg for the fuel used, and C [kg/m^2] is the specific fuel load (Weise & Biging, 1996).

3.4.2. Flame Height

As described previously, this parameter was determined by measuring the fire front in a series of frames throughout each test (Figure 3.10). With these frames was possible to draw a line corresponding to the flame plane and make the measurements using *Microsoft Office* tools to calculate the height of the flames.

Figure 3.10 Lateral Image of the Fire.

3.4.3. Temperatures and heat flux

The temperatures and heat flux were recorded, saved in the NI System, and converted into *Microsoft Excel®* directly. For data acquisition, an NI chassis cDag 9174 acquisition board with a 9213 temperature input module, a 9211 voltage input module and a computer with the Signal Express program with an acquisition frequency of 1 Hz were used.

The temperatures were recorded by three type K thermocouples located on the cabinet. The heat flow record was obtained using the flowmeter mounted on the front side of the cabinet. To obtain the correct flow rate values, it was necessary to correct the value read by the flowmeter itself. It was needed to consult the flowmeter user manual (*Hukseflux IHF01*), from which equation (3.4) was obtained:

$$\Phi = \frac{U}{(S \times (1 - 0{,}0005 \times (T - 20))} \qquad (3.4)$$

Where Φ $[W/m^2]$ is the heat flux, U [V] is the voltage output, S [V/(W/m^2)] is the calibration sensitivity value, which according to the manual is equal to 9.83×10^{-9} V/(W/m^2), and T [℃] is the temperature.

4. ANALYSIS AND DISCUSSION

Several tests were carried out to evaluate how this active protection system work as a function of the wind speed and to understand the influence of different angles of the sprinklers on the attenuating of the fire front propagation and intensity.

As said previously the ROS was measured by the IR images taken on the lifting platform, and the height of the flames was determined through the videos from the side camera. This set of images and the data obtained by the thermocouples and flowmeter were fundamental for the analysis of the experimental tests.

Tests were carried out for wind speed, U of 0, 1, and 2 m/s, with or without the fan blinds open to test the designed autonomous active protection system on fire intensity control. All experimental tests, images and sensor data were processed in *Microsoft Office*® tools and by a software called *Fire ROS Calculator*.

4.1. Rate of Fire Spread

ROS was studied by measuring the fire front in a series of frames, to see the fire spread over time. To evaluate the performance of the autonomous protection system was calculated the rate of spread for different wind speeds scenarios.

Figure 4.1 shows the rate of spread, nondimensional, as a function of the time in seconds for the first four tests with the active protection system working. The values of the rate of spread were obtained by dividing the ROS, in cm/s, by the average ROS obtained in the reference test. This benchmark test corresponds to the first test performed without wind and the active protection system activation.

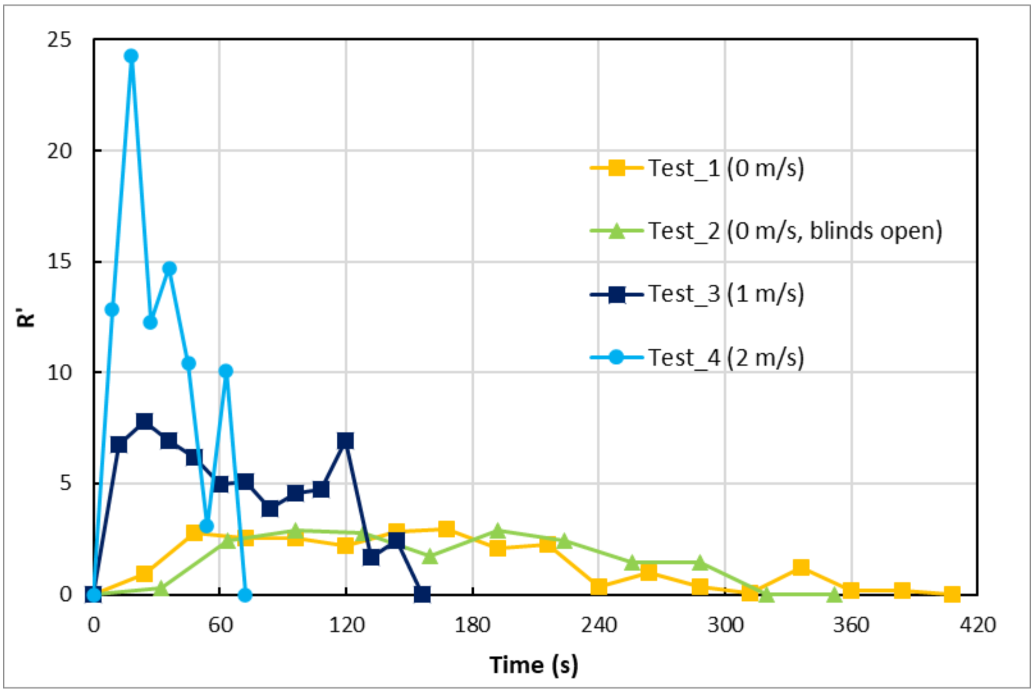

Figure 4.1 Rate of spread as a function of time for test 1, 2, 3 and 4.

As described in table 3.1, experimental tests 1 and 2 were performed with 0 m/s flow velocity, but with the blinds open in the second test. The third and fourth experimental tests were performed with wind speed velocities of 1 m/s and 2 m/s, respectively.

It is noticeable from the analysis of figure 4.1 that the rate of spread increases significantly with wind speed. The high values of the rate of spread at the beginning of the test, when the wind speed is bigger, are mainly due to the ignition system used. It is visible that over time the influence of the wind decreases, this supports the idea that when the wind direction is the same as the fire propagation, the rate of spread increases dramatically (Viegas, 2006).

So, the different wind speeds in the combustion tunnel ranging from 0 to 2 m/s, have a direct influence on the ROS, causing significant changes for each experimental test. Without wind, the ROS is much more constant, and the experimental tests take longer to finish because the fire takes longer to propagate through the fuel bed.

It is also shown that the ROS for a fuel bed without borders has a lot of volatility, which is detected by the significantly varied values from one moment to the next for the same wind speed, as it was concluded by Jesus (2021) and Ribeiro et al. (2022).

Another analysis made was regarding the effect of the angle of the sprinklers above the telecommunication cabinet along the vertical axis. Figure 4.2 shows the results obtained for the three sprinkler scenarios studied with a wind speed of 1 m/s, with the sprinklers at 45° on the third test, 0° on the fifth test, and 90° on the sixth test. The ROS under examination corresponds to an imaginary line of propagation in the middle of the fuel bed.

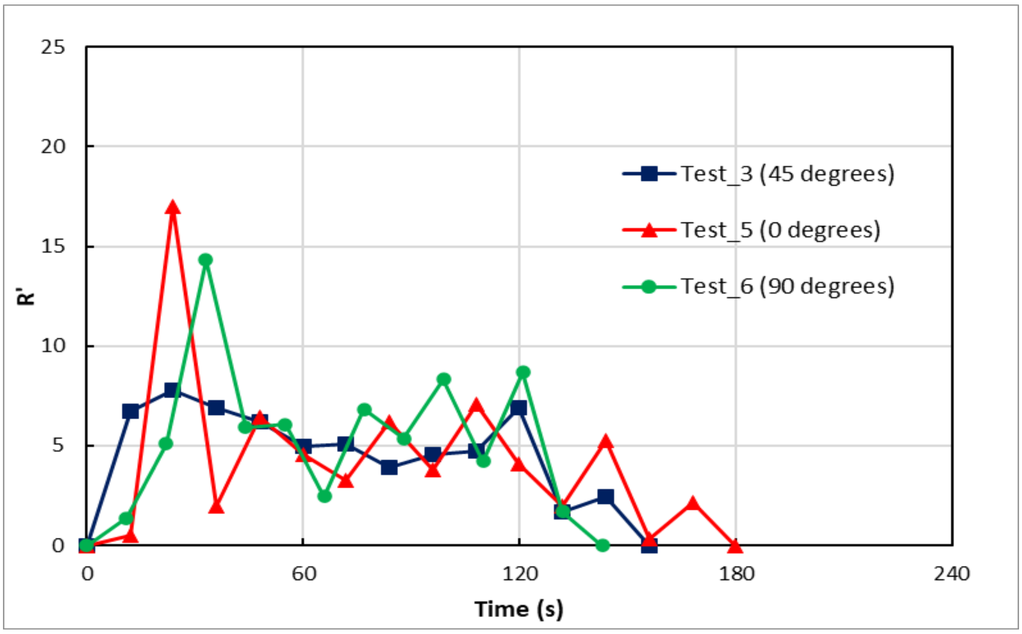

Figure 4.2 Fire rate of spread for three different angles of sprinklers.

In Figure 4.2 it is possible to see that when the sprinklers are at 90º the ROS stopped propagating faster than in the other two situations. This happens because, with the sprinklers inclined at 90 degrees to the vertical, the mist caused by the sprinklers covers a larger area than in the other two positions. It can also be seen that when the sprinklers are inclined directly towards the cabinet, in the fifth test, the fire propagation ends twenty seconds later.

It can also be seen that even though the same wind speed is applied in all three trials the ROS in the initial instants is somewhat different, it only stabilises after 40 seconds.

For a more accurate analysis of the ROS, it was important to study the entire width of the fuel bed to see which was the best sprinkler configuration. So, this way was examined the ROS with three different fuel bed lines of propagation.

In Figure 4.3, it's possible to see the three lines used to analyse each test, one on top, in the middle and one on the bottom, when viewed from above, of the fuel bed.

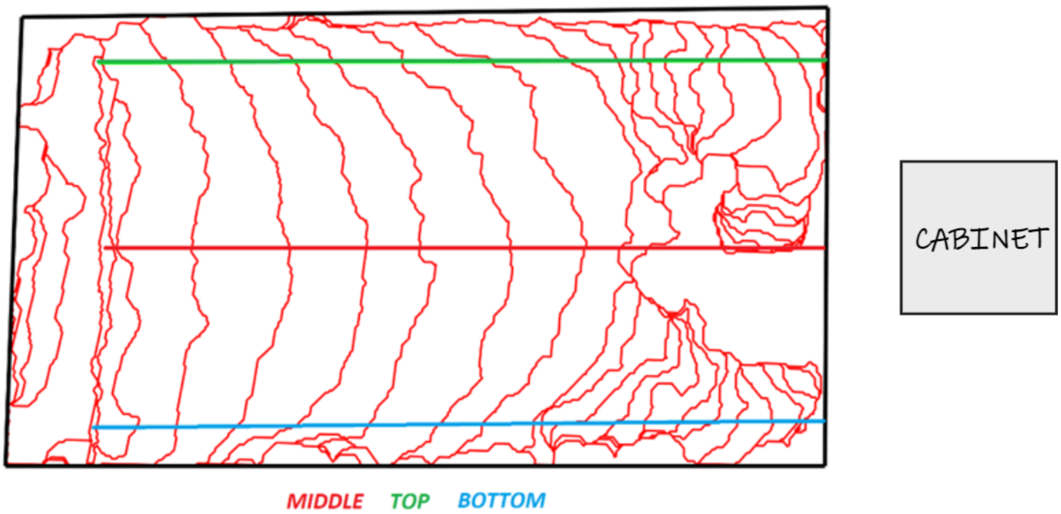

Figure 4.3 The three lines used for ROS analysis were taken with the *Fire ROS Calculator*.

As shown, the ROS was studied in three different positions to understand the sprinklers' effect on controlling the flames. Therefore, the ROS in all these fuel bed lines was calculated through the software *Fire ROS Calculator*. Thus, three groups of results were considered for analysing each test.

The following graphs, Figure 4.4 to Figure 4.6, represent the values obtained in the three experimental trials that can be compared easily because all of them were carried out with a wind speed of 1 m/s but with three different sprinkler inclinations.

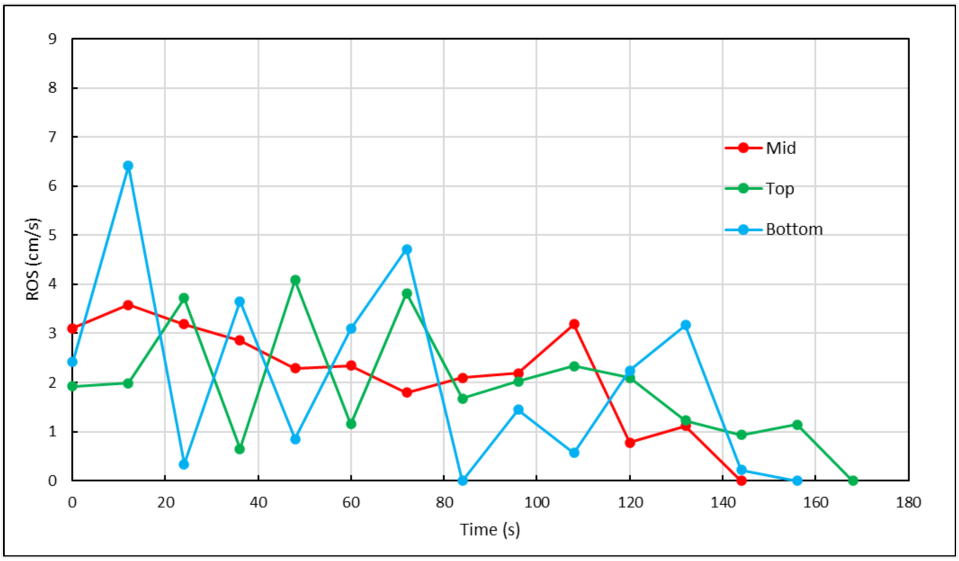

Figure 4.4 ROS of the 3 spread lines for the 45° angle of the sprinklers in the third test.

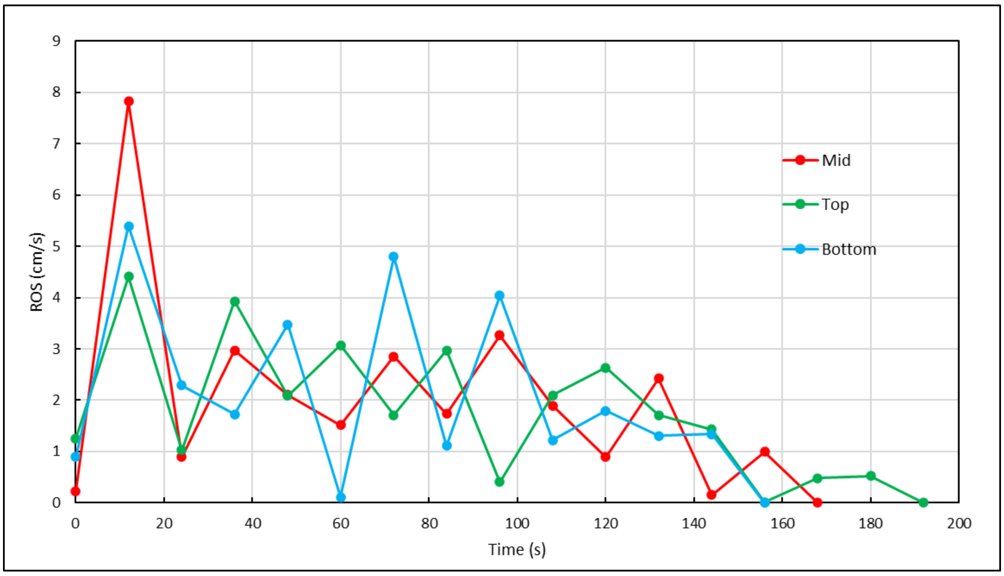

Figure 4.5 ROS of the 3 spread lines for the 0º angle of the sprinklers in the fifth test.

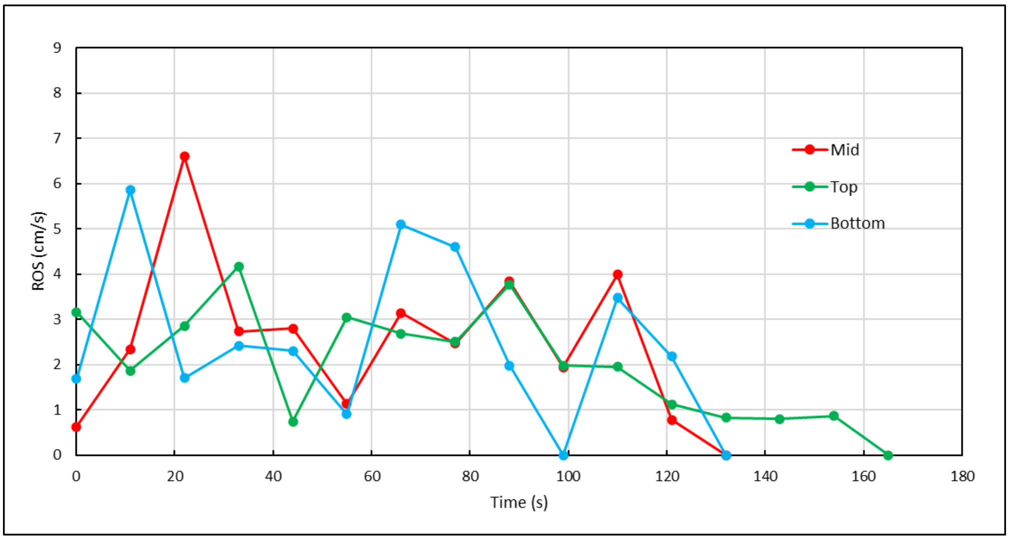

Figure 4.6 ROS of the 3 spread lines for the 90º angle in the six test.

Through these results, it is possible to verify that as it had been thought the best position of the sprinklers to control the fire quicker is when the sprinklers are placed at 45 degrees relative to the vertical axis. It was verified that in this situation the central line from the fuel bed ROS analysis, closed to the cabinet, is controlled faster than the outer lines.

Another conclusion that can be drawn from the graphs is that when the sprinklers are placed facing downwards, with 0 degrees of inclination, the results obtained show that the system is not able to slow down the fire as much as in the other two situations. So, this inclination of the sprinklers seems to be the worst solution of the three hypotheses.

4.2. Fireline Intensity

Fireline intensity was the second parameter for analysis. To make these measurements it was used equation (3.3) which multiplies the ROS by the heat yield and the fuel load of each experimental test.

Through this equation, it’s seen that the fireline intensity is proportional to the ROS, therefore this parameter should have the same graphic arrangement as the figures shown previously.

Figure 4.7 shows the fireline intensity graph for each one of the experimental tests done with different flow velocities imposed.

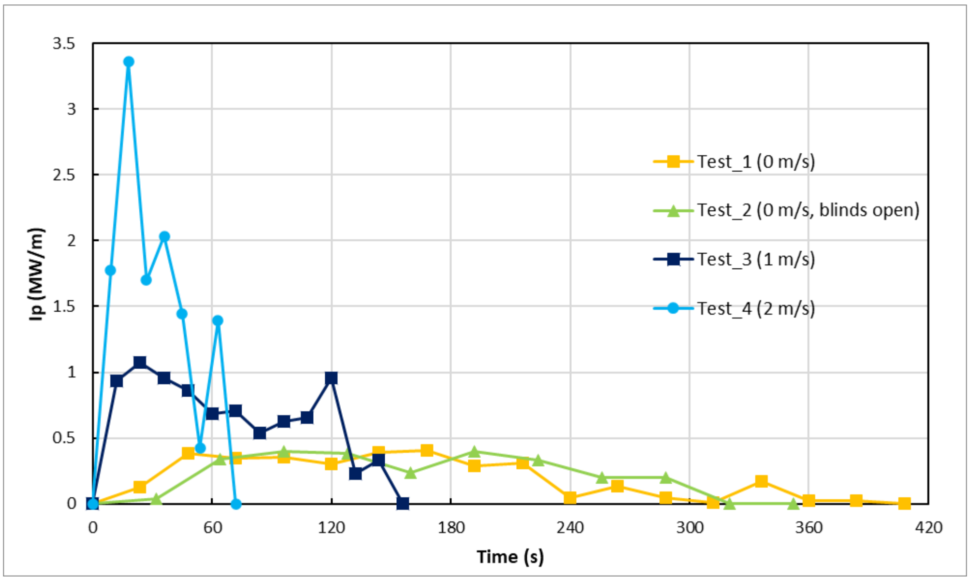

Figure 4.7 Fireline Intensity Values for tests 1, 2, 3 and 4.

A point to note is that, like in the ROS software analysis which has a measurement error margin of ±5%, the error that is associated with increasing flow velocities also increases. This demonstrates that the intensity of a fireline grows as the flow velocity increases, as long as the wind direction is the same as the fire's spread.

It can also be seen that the values achieved for the fireline intensity are high fire front intensity values (2 to 4 MW/m) which prove that the protection system used is tested for high demanding conditions where the rate of spread is moderate to high (Alexander and Cruz, 2019).

4.3. Flame Height

Another aspect to consider when studying the results obtained from these experimental tests was the analysis of the flame height.

The flame heights of all tests were compiled and split by the different flow velocities (0, 1 and 2 m/s) for this research. Figure 4.8 shows how the height of the flame is represented for the four tests with the sprinklers at the same angle but for different flow velocities.

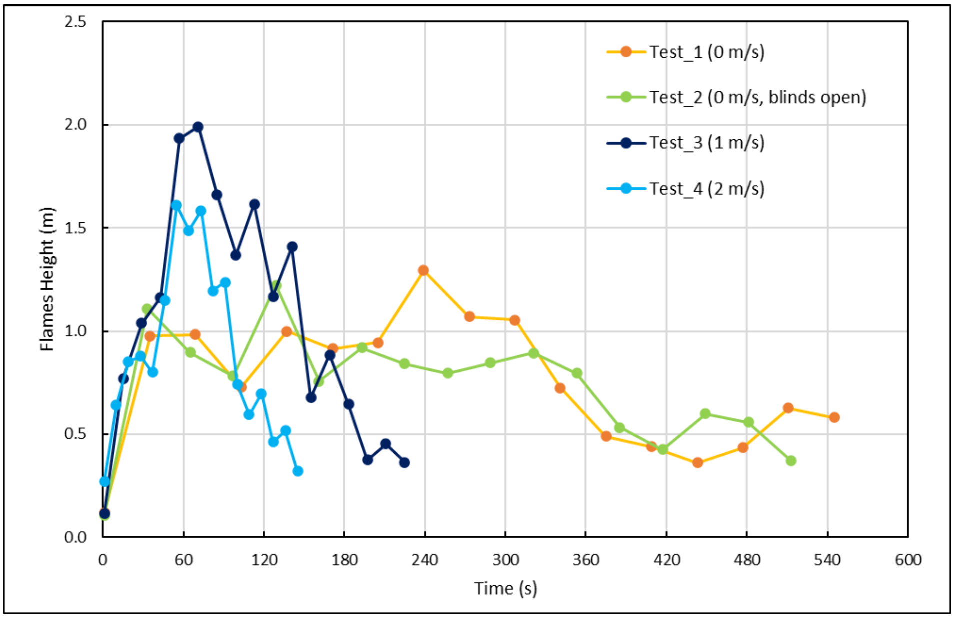

Figure 4.8 Heights of flames for different flow velocities.

Figure 4.8 demonstrates an interesting fact, the height of the flames in the fourth test, which was carried out with a wind speed equal to 2 m/s, reaches a lower height of the flames than in test 3, which was carried out with a lower wind speed, equal to 1 m/s. This happens because the test with higher wind speed makes the fuel be consumed faster and therefore the flames stop growing too quickly because they have no more fuel to burn.

To further compare, flame height measurements were also taken for the experimental trials in which the sprinklers were placed at different inclinations.

The following graph, Figure 4.9, demonstrates the flame heights for these three experimental tests.

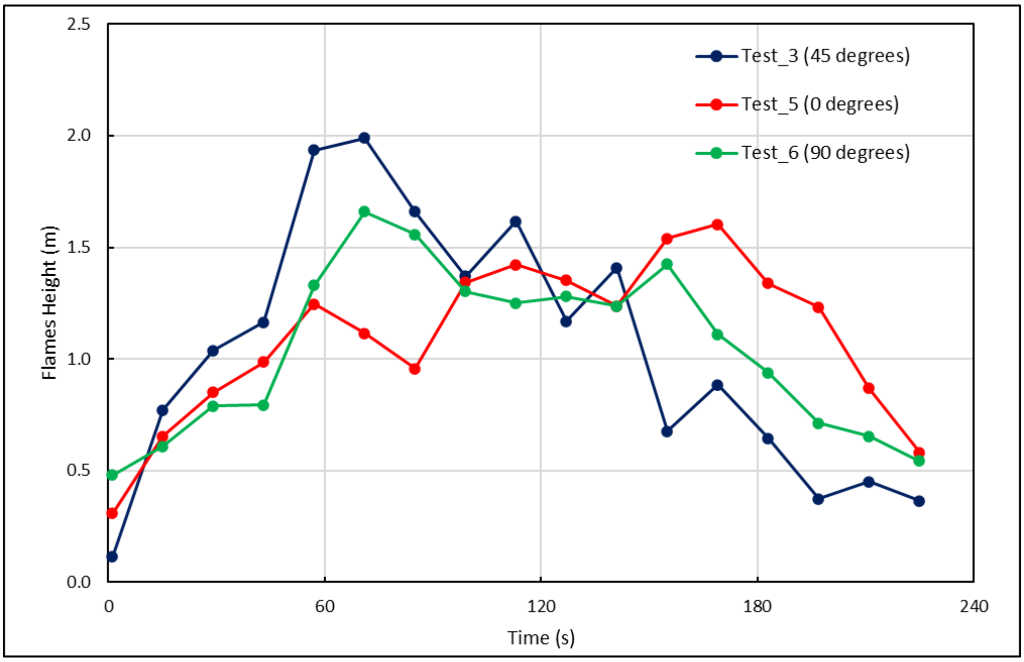

Figure 4.9 Different heights of flames for the three different sprinklers angles.

With the observation of the figure, we can notice that the height of the flames in the experimental test with the sprinklers making 45 degrees angle with the vertical axis (third experimental test) is smaller than in the other two experiments when it is close to the telecommunication cabinet and consequently within the radius of action of the sprinklers. Although at the beginning of the test, it can be seen the height of the flames in the third test was higher.

This way the built system efficiently fulfils the objective of containing the flames and it is possible to ensure that the 45 degrees angle of the sprinklers should be the most effective. Another conclusion that can be drawn from this graph is that when the sprinklers are placed at 0 degrees (fifth test) the height of the flames reduces much less, so this is another element that proves that this is the worst solution of the three positions tested.

4.4. Temperature and Flow Heat

For the analysis of the temperatures in the cabinet, the data acquired with NI System, provided by the installed thermocouples and the flowmeter were used. Although four thermocouples were installed to make the measurements of the temperatures on the cabinet, in the graphs shown below just three of them were used. The first one (T1) was installed 50 cm above the ground on the cabinet surface, the second one (T2) was the temperatures measured by the flowmeter, set on the cabinet surface 75 cm above the ground, and the last one measured the laboratory temperature (Tlab).

The figures below, Figure 4.10 to Figure 4.14, show the temperatures obtained in the NI System for the reference test and the four different flow velocities tests.

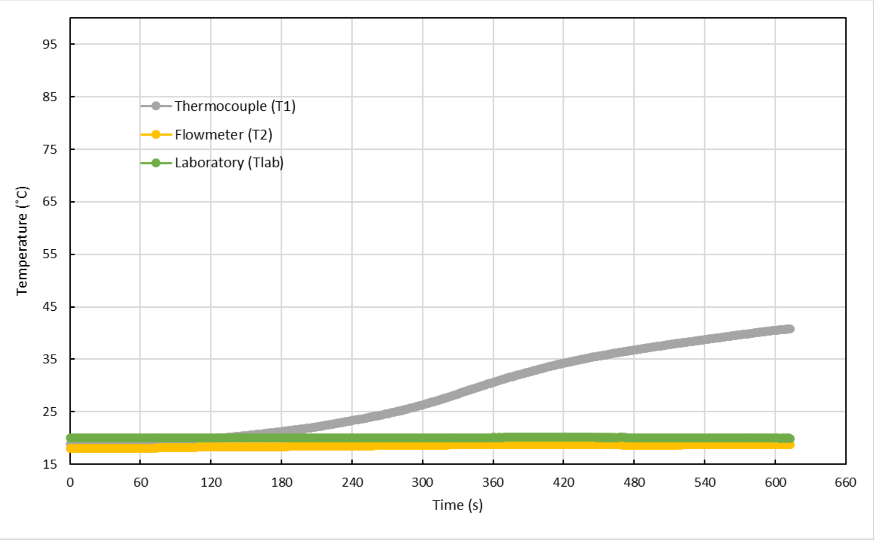

Figure 4.10 Evolution of temperatures for the reference test (U=0 m/s).

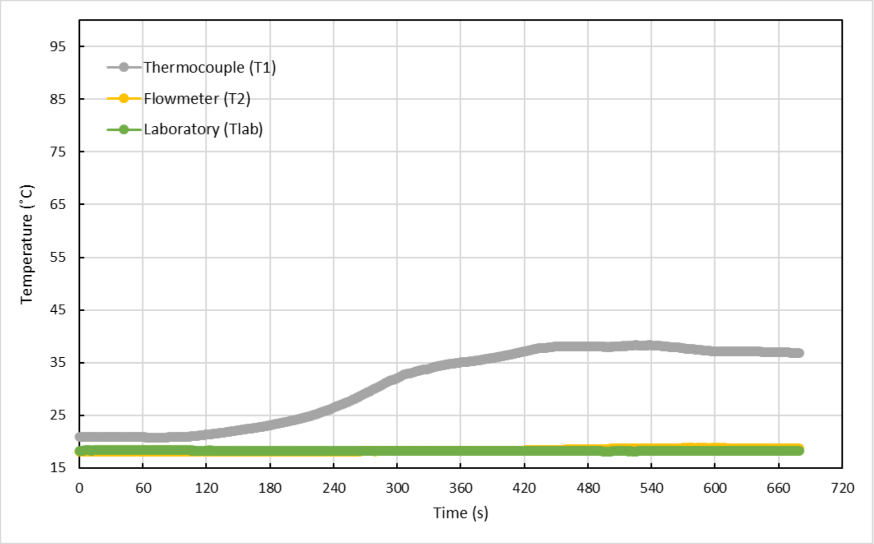

Figure 4.11 Evolution of temperatures of test 1 (U=0 m/s).

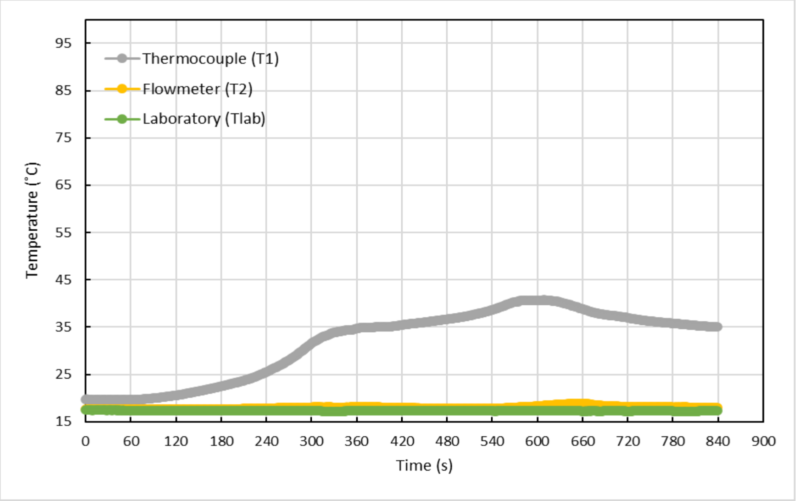

Figure 4.12 Evolution of temperatures of test 2 (U=0 m/s, blinds open).

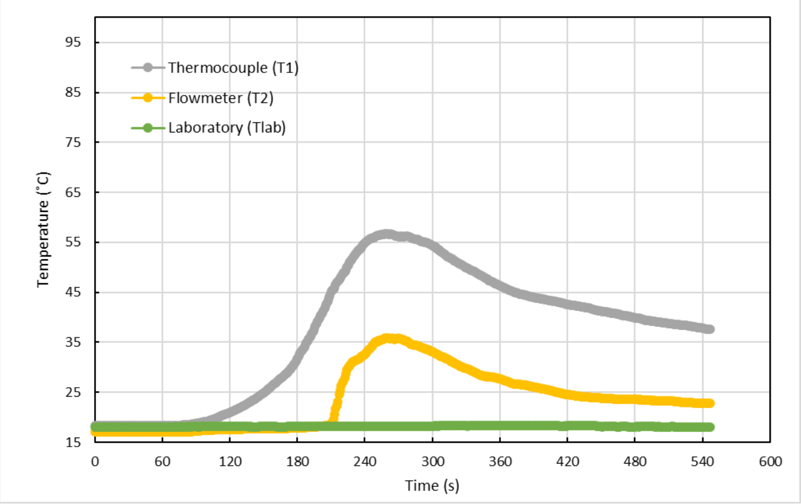

Figure 4.13 Evolution of temperatures of test 3 (U=1 m/s).

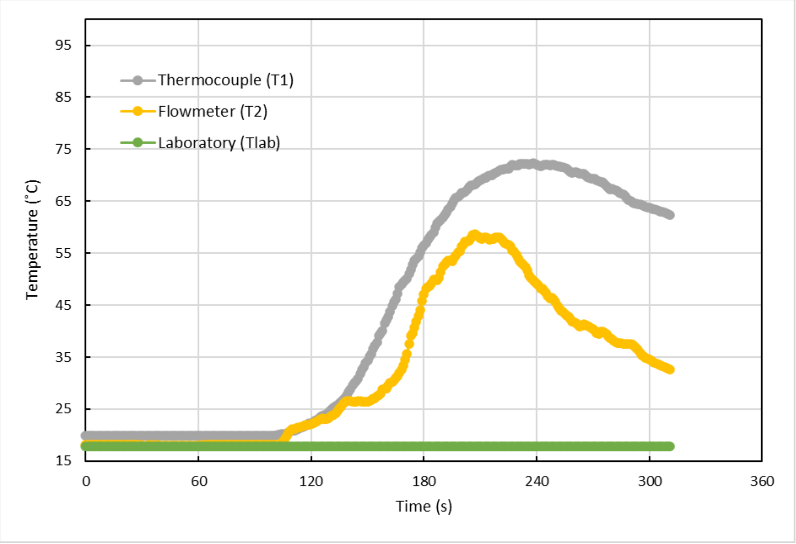

Figure 4.14 Evolution of temperatures of test 4 (U=2 m/s).

From the analysis of the figures presented it is possible to verify the high impact of wind speed on the temperature range reached in each experimental test. One example of this can be the comparison between the first three figures and the last two (Figure 4.13 and Figure 4.14), where the range of temperatures that were read by the sensors is higher in the last two figures which have bigger flow velocities.

To also understand the impact of sprinkler position on the temperatures obtained by the sensors in the cabinet surface the figures 4.15 and 4.16 present the temperatures for the two last experimental tests with different sprinkler angles. These figure can be compared with Figure 4.14 which was obtained for the same test conditions.

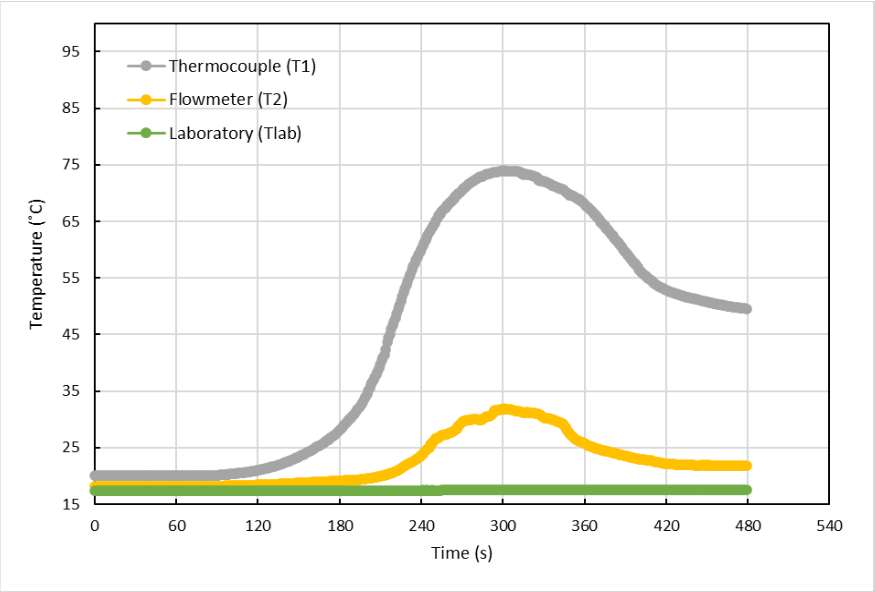

Figure 4.15 Evolution of temperatures of test 5 with the sprinklers in a 0° angle (U=1 m/s).

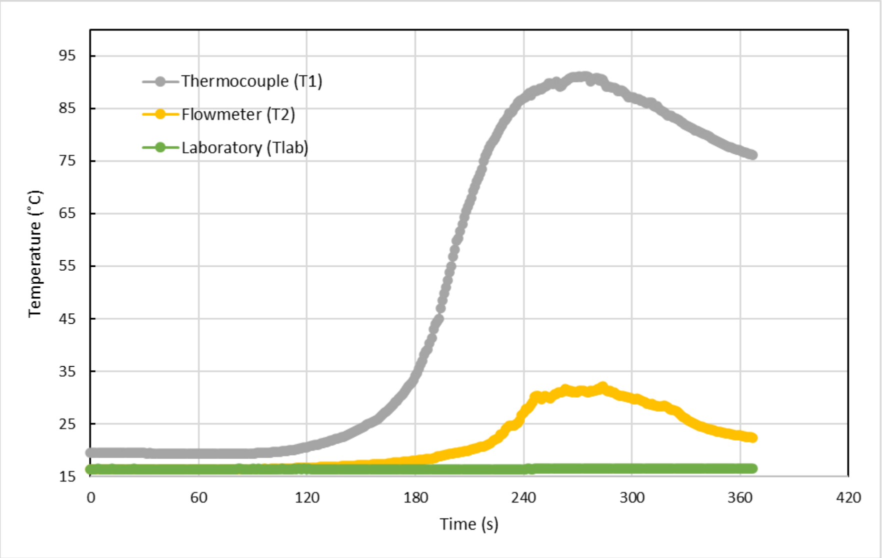

Figure 4.16 Evolution of temperatures of test 6 with the sprinklers at a 90° angle (U=1 m/s).

Comparing the figures of the tests with the different sprinkler positions we can see that when the sprinklers are placed in a different position from 45º degrees the temperatures in the telecommunication cabinet are higher. In the case of sprinklers placed with an angle of 0 degrees (test 5) this happens because there is not, as already seen, an area of action of the sprinklers, then simply the water is wetting the cabinet. In the case of sprinklers placed at 90 degrees to the vertical (test 6), the temperature is higher because as these sprinklers are pouring the water over a very large area the particle density is too low and also the impact of the wind disperses these small particles which therefore have no impact on the temperature reduction.

4.5. Compilation and discussion of results

In this subchapter, all the results obtained were compiled and then compared to be able to draw some conclusions. Before proceeding to make conclusions, in Table 4.1 we can see the results obtained from the maximum and some average values of the parameters previously analysed.

Table 4.1 Compilation of the variables and results under study.

Experimental Tests	Wind velocity (m/s)	Blinds	Sprinkler angle (˚)	$T_{máx}$ surface of the cabinet (˚C)	$T_{máx}$ / T_{amb}	$R'_{máx}$	$I_{máx}$ (MW/m)	Flame height average (m)
Test 0	0	*Close*	-	40.79	2.03	1.15	0.35	1.103
Test 1	0	*Close*	45	38.33	2.10	2.95	0.41	0.749
Test 2	0	*Open*	45	40.76	2.36	2.91	0.40	0.732
Test 3	1	*Open*	45	56.81	3.13	7.77	1.07	1.037
Test 4	2	*Open*	45	72.39	4.05	24.29	3.36	0.885
Test 5	1	*Open*	0	73.99	4.24	16.97	2.35	1.096
Test 6	1	*Open*	90	91.22	5.55	14.32	1.98	1.040

Through this table, it is possible to draw some conclusions due to the values obtained for each of the tests. As an example, through the maximum temperatures obtained on the last two tests, where the sprinklers were placed at different inclination angles, the temperatures measured by the thermocouple on the cabinet surface are higher than for example in the case where a higher wind speed is applied.

Regarding the analysis of temperatures, Figure 4.17, shows the difference between a test with the application of the active protection system and one without the system, which was the reference test.

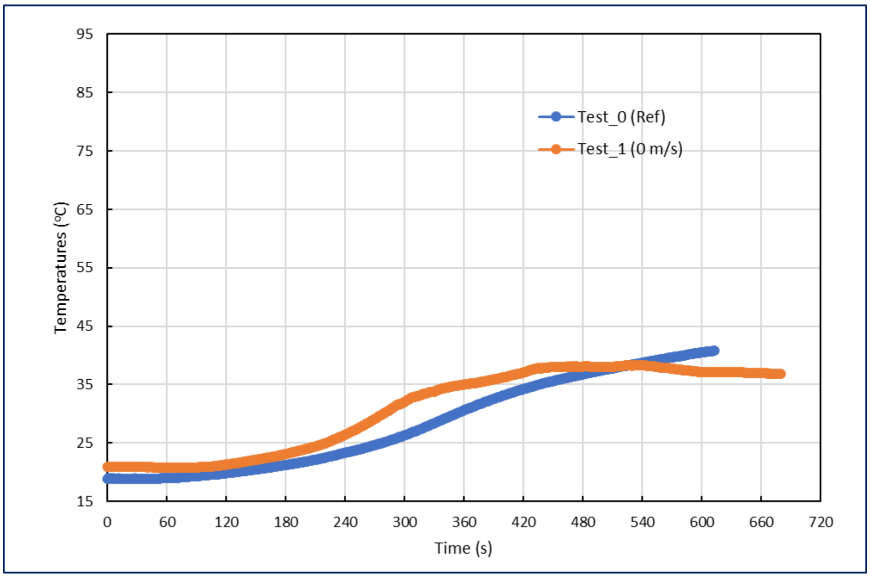

Figure 4.17 Comparison between temperatures in tests with and without the active protective system.

In this figure, it is possible to see the impact that the autonomous protection system has in reducing the temperature read on the surface of the cabinet. While in the test in which the protection system was not active the temperature read on the surface of the cabinet was always rising, in the experimental test in which the protection system was activated the temperature decreased at the end of the test. This fact proves that the application of sprinklers affects the temperature of the cabinet, reducing it.

Figure 4.18 demonstrates the differences caused by the various inclinations of the sprinklers under the same test conditions. Through the following figure, it is possible to see that the correct application of this autonomous protection system, which happens with the sprinklers at 45 degrees, is an effective mechanism for the protection of the telecommunication cabinets.

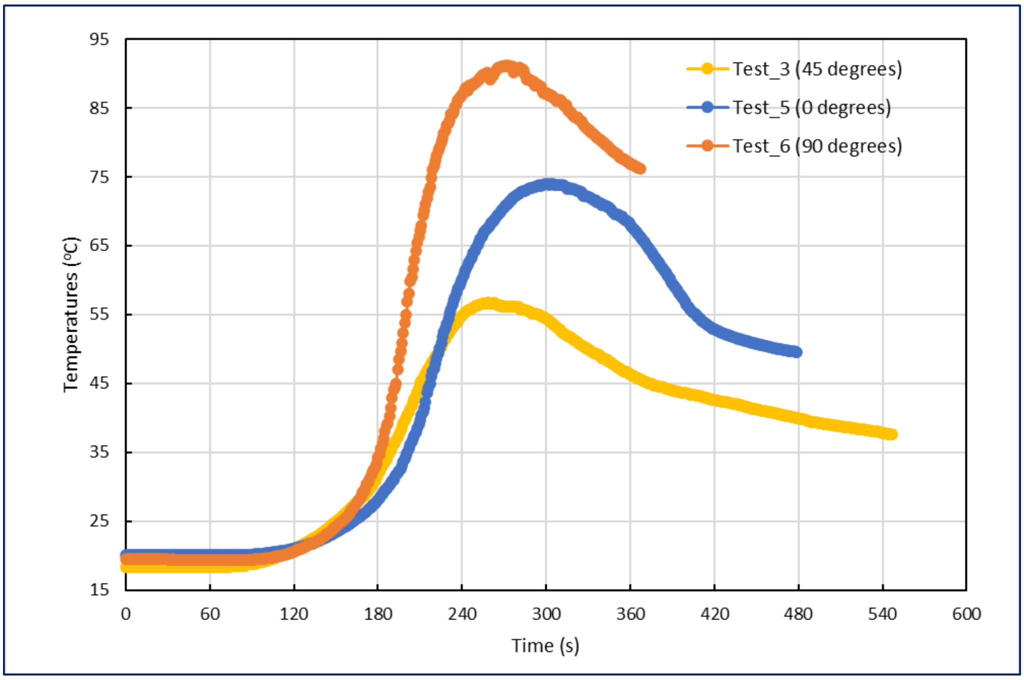

Figure 4.18 Comparison between temperatures in tests with the sprinklers at different angles.

Another aspect to be taken into account to understand the efficiency of this mechanism is the conclusions taken from the rate of spread analysis along the entire width of the fuel bed. Figure 4.19 shows the three propagation lines for the fourth test that was made with a wind speed equal to 2 m/s.

In figure 4.19, it is possible to verify that, even for the highest wind intensity, the central propagation line, which is the one where there is a greater amount of sprinkler application, finishes propagating earlier than the others. This proves that this system works in the protection of the telecommunication cabinet.

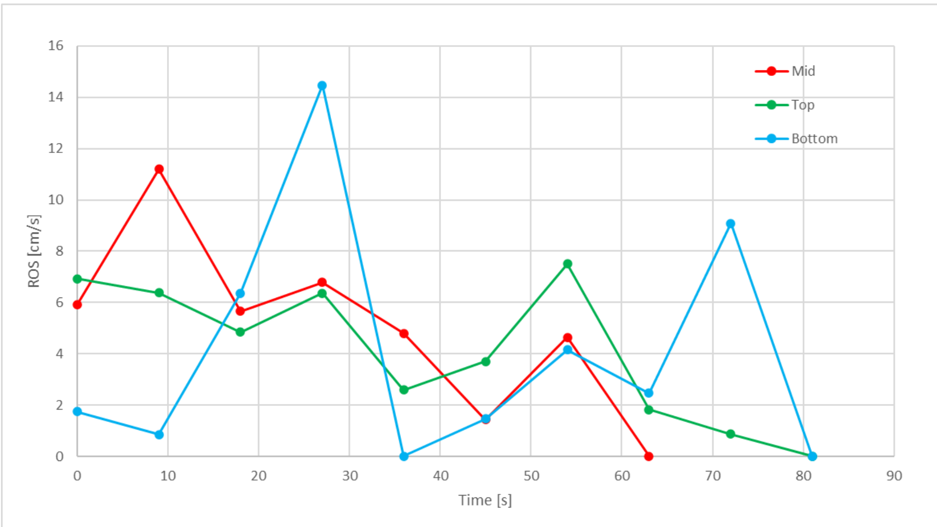

Figure 4.19 ROS of the 3 spread lines in the four test, with 2 m/s wind speed.

The software used to calculate the ROS allowed us to calculate the average values for the rate of spread along three horizontal lines along the fuel bed, as well as the sum and maximum value of the ROS. These values, in cm/s, are represented in the tables below, from Table 4.2 to Table 4.4.

Table 4.2 Values for the test with and without active protection system activated (cm/s).

	Test_0			Test_1		
Lines	Max	Sum	Ave	Max	Sum	Ave
Top	1.03	10.88	0.51	1.47	10.35	0.58
Middle	1.15	10.36	0.46	1.36	11.25	0.48
Bottom	1.08	11.14	0.50	1.54	13.84	0.59

Table 4.3 Values for the four tests with different wind speeds (cm/s).

	Test_1			Test_2			Test_3			Test_4		
Lines	Max	Sum	Ave	Max	Sum	Ave	Max	Sum	Ave	Max	Sum	Ave
Top	1.47	10.35	0.58	1.23	10.78	0.49	4.09	28.77	1.22	7.51	41.01	1.58
Middle	1.36	11.25	0.48	1.34	8.43	0.33	3.58	28.52	1.07	11.20	40.43	1.36
Bottom	1.54	13.84	0.59	1.23	10.82	0.48	6.42	29.12	1.09	14.48	40.62	1.92

Table 4.4 Values for the three trials with different sprinkler inclinations (cm/s).

	Test_3			Test_5			Test_6		
Lines	Max	Sum	Ave	Max	Sum	Ave	Max	Sum	Ave
Top	4.09	28.77	1.22	4.41	29.74	1.31	4.17	32.42	1.43
Middle	3.58	28.52	1.07	7.82	29.75	1.27	6.60	32.43	1.44
Bottom	6.42	29.12	1.09	5.39	29.50	1.28	5.86	32.25	1.39

Based on the values obtained and displayed in the previous tables, some conclusions can be drawn. The first conclusion is that when the sprinklers were placed with a 45^{o} inclination (in the first 5 tests), and when these sprinklers were activated (all of the tests except the first one), the ROS in the middle row was always lower than the other two lines. Another aspect was that the higher the wind speed, the greater the difference between the highest average obtained from the three lines and the average obtained for the middle line. This proves to be yet another example of the system's ability to reduce fire intensity.

The sum of the ROS also demonstrates that in the middle line, where there are more sprinklers and in which the greatest protection focus is, the sum is smaller, even though sometimes the maximum propagation value is obtained in this line.

Finally, the flame height is another factor that demonstrates the ability of sprinklers to reduce the intensity of flames. Like it can be seen in Figure 4.9, for the same test conditions, when the sprinklers are placed in the correct position (45 degrees), the impact of reducing the height of the flames is significant.

5. CONCLUSIONS

The objective of this work was to develop and understand what the ability of an active protection system would be to protect a telecommunication cabinet autonomously.

To carry out this study, we started by understanding the best way to build a simple system capable of responding autonomously to the presence of a fire, as well as being effective in protecting the telecommunications cabinet. For this, an Arduino board was programmed to trigger the release of water mist by a set of six sprinklers arranged above the cabinet.

The first thing that was verified was the need to have several temperature sensors placed in strategic positions and far enough away for the fire to be detected in advance. Another detail considered later in the programming of this system was the attention to the undue outflow of the extinguishing agent, which in this case was water. To prevent undue expenses, the software was designed in such a way that whenever the fire ceased to be a threat, after the fire was detected and controlled, the electro valve that allowed the release of water was closed.

After making the autonomous system and the structure mounted on top of the cabinet face exposed to fire, experimental tests were carried out for different types of conditions. The results obtained through these tests prove to be quite satisfactory regarding the ability of this protection mechanism. These experimental tests, despite having been carried out in a laboratory, created a high fireline intensity that also proved to be possible to contain by the built sprinkler system.

The results obtained, demonstrate that the sprinkler system proved to be quite effective in reducing the rate of spread near the telecommunications cabinet, as well as the temperatures that were measured on the cabinet. Another very important aspect that was found to be quite smoothed out was the height of the flames, which was found to be greatly affected using this autonomous water sprinkler mechanism. This conclusion was made for the sprinkler installation with a 45° inclination with a vertical axis. This configuration, as can be seen by reading subchapter 4.5, proved to be the most favourable for desired protection.

These results led us to conclude that it is possible to protect a telecommunication cabinet with an active fire protection system.

This work had some limitations such as the fact that more tests with different types of fuel and more tests with higher wind speeds should be done.

To improve this study, it was interesting to test other elements in this system, such as the placement of remote control that allowed activating or deactivating the release of water, or for example, placing a smaller number of sprinklers at a different height above the cabinet to test if it would be possible obtain equally satisfactory results but with less water.

A suggestion for future work would be to install a module on the Arduino board that would make it possible to save the data obtained on an SD card. Another possible experiment to be done would be to test on the autonomous system with a flame detector, this system may not be that beneficial as it may induce some activation errors.

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APPENDIX A - AUTONOMOUS SYSTEM CONNECTIONS

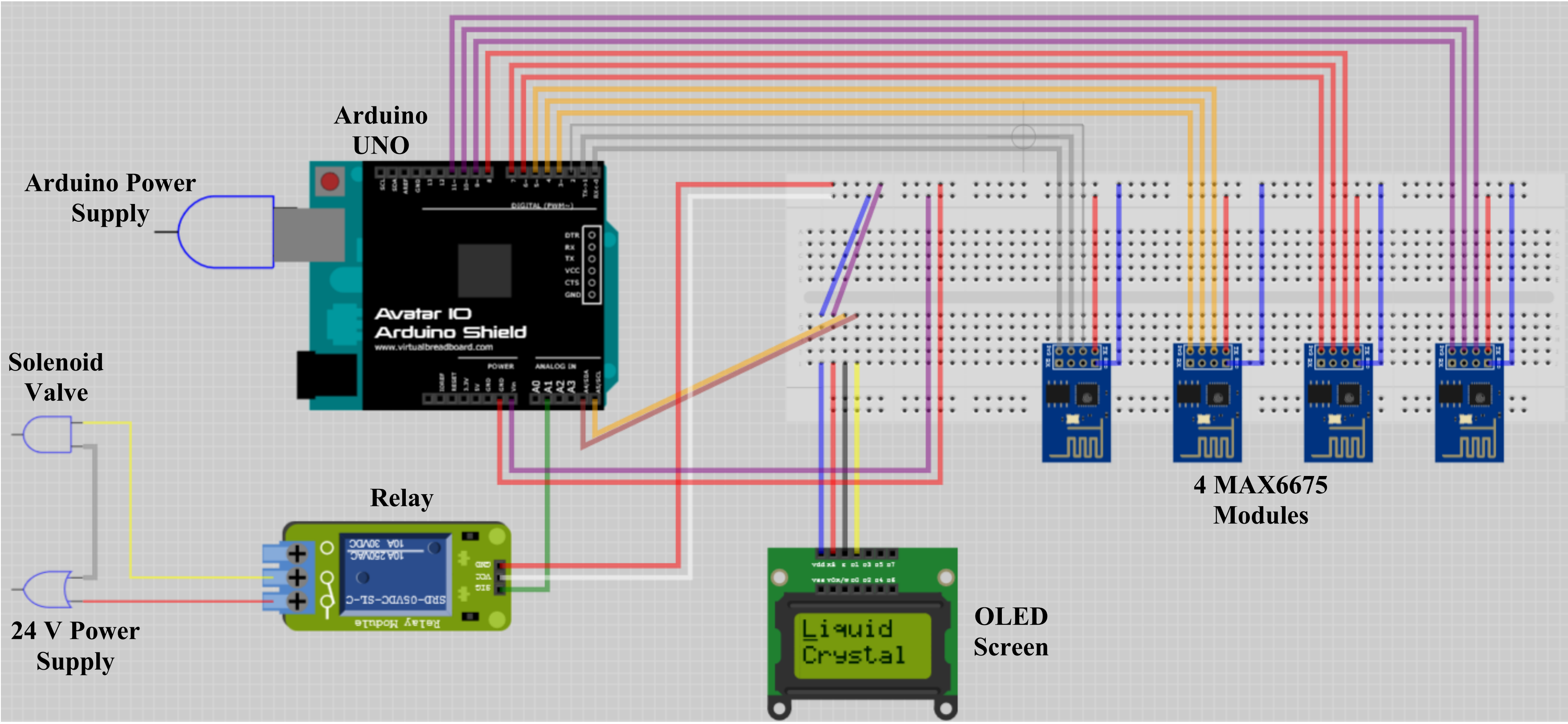

Figure A.1 Configuration of the autonomous system.

APPENDIX B - ARDUINO CODE

```
#include "max6675.h"
#include <Adafruit_GFX.h>
#include <Adafruit_SH1106.h>
#include <Adafruit_Sensor.h>

#define SCREEN_WIDTH 128 // OLED display width, in pixels
#define SCREEN_HEIGHT 64 // OLED display height, in pixels
#define OLED_RESET -1
Adafruit_SH1106 display(OLED_RESET);

const int RELAY1 = A1;

// Temperature Sensor1
int thermo1D0 = 13; // so
int thermo1CS = 12;
int thermo1CLK = 11; // sck
float temp1 = 0;
MAX6675 thermocouple1(thermo1CLK, thermo1CS, thermo1D0);

// Temperature Sensor2
int thermo2D0 = 10; // so
int thermo2CS = 9;
int thermo2CLK = 8; // sck
float temp2 = 0;
MAX6675 thermocouple2(thermo2CLK, thermo2CS, thermo2D0);

// Temperature Sensor3
int thermo3D0 = 7; // so
int thermo3CS = 6;
int thermo3CLK = 5; // sck
float temp3 = 0;
MAX6675 thermocouple3(thermo3CLK, thermo3CS, thermo3D0);
```

```
// Temperature Sensor4
int thermo4D0 = 4; // so
int thermo4CS = 3;
int thermo4CLK = 2; // sck
float temp4 = 0;
MAX6675 thermocouple4(thermo4CLK, thermo4CS, thermo4D0);

void setup()
{
  Serial.begin(9600);
  display.begin(SH1106_SWITCHCAPVCC, 0x3C);
  delay(1000);
  display.clearDisplay();
  display.setTextColor(WHITE);

// Setup Relay
  pinMode(RELAY1, OUTPUT);
  digitalWrite(RELAY1, LOW);
  }
void loop()
{
  double temp1 = thermocouple1.readCelsius();
  double temp2 = thermocouple2.readCelsius();
  double temp3 = thermocouple3.readCelsius();
  double temp4 = thermocouple4.readCelsius();

  Serial.print("C1 = ");
  Serial.println(temp1);
  Serial.print("C2 = ");
  Serial.println(temp2);
  Serial.print("C3 = ");
  Serial.println(temp3);
  Serial.print("C4 = ");
  Serial.println(temp4);
```

```
//clear display
  display.clearDisplay();

// temperature sensor 1
  display.setTextSize(1);
  display.setCursor(0,0);
  display.print("Temp1: ");
  display.setTextSize(1);
  display.setCursor(38,0);
  display.print(temp1);
  display.print(" ");
  display.setTextSize(1);
  display.cp437(true);
  display.write(167);
  display.setTextSize(1);
  display.print("C");

// temperature sensor 2
  display.setTextSize(1);
  display.setCursor(0,20);
  display.print("Temp2: ");
  display.setTextSize(1);
  display.setCursor(38,20);
  display.print(temp2);
  display.print(" ");
  display.setTextSize(1);
  display.cp437(true);
  display.write(167);
  display.setTextSize(1);
  display.print("C");
```

```
// temperature sensor 3
  display.setTextSize(1);
  display.setCursor(0,40);
  display.print("Temp3: ");
  display.setTextSize(1);
  display.setCursor(38,40);
  display.print(temp3);
  display.print(" ");
  display.setTextSize(1);
  display.cp437(true);
  display.write(167);
  display.setTextSize(1);
  display.print("C");

// temperature sensor 4
  display.setTextSize(1);
  display.setCursor(0,57);
  display.print("Temp4: ");
  display.setTextSize(1);
  display.setCursor(38,57);
  display.print(temp4);
  display.print(" ");
  display.setTextSize(1);
  display.cp437(true);
  display.write(167);

  display.setTextSize(1);
  display.print("C");
  display.display();
```

```
// Função
  if(temp1 >= 35 || temp2 >= 35 || temp3 >= 35 || temp4 >= 35){
    digitalWrite(RELAY1, HIGH);
    Serial.println("Relay ON");
  }
  else{
    digitalWrite(RELAY1, LOW);
    Serial.println("Relay OFF");
  }
  delay(1000);
}
```

APPENDIX C - RATE OF SPREAD FIGURES

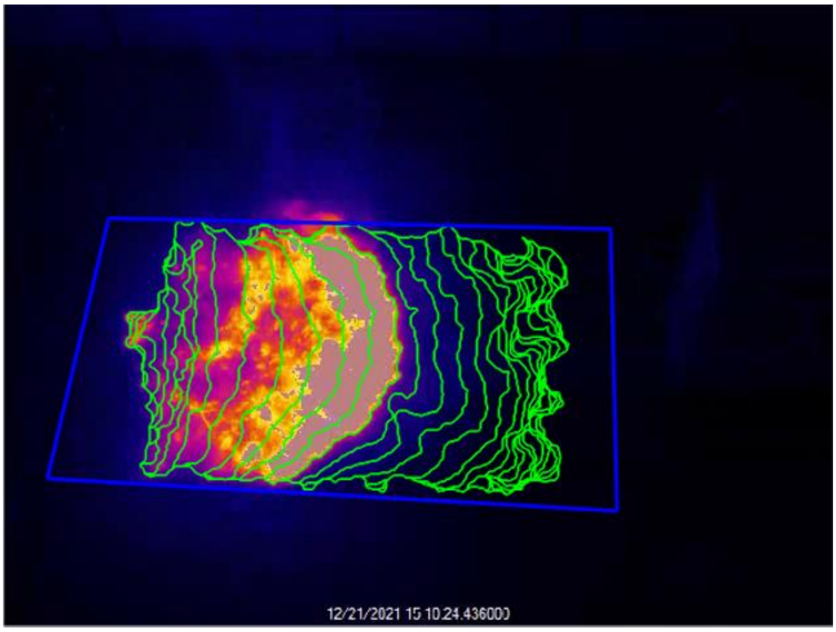

Figure C.1 Image of the rate of spread of the IR camera from Test 0.

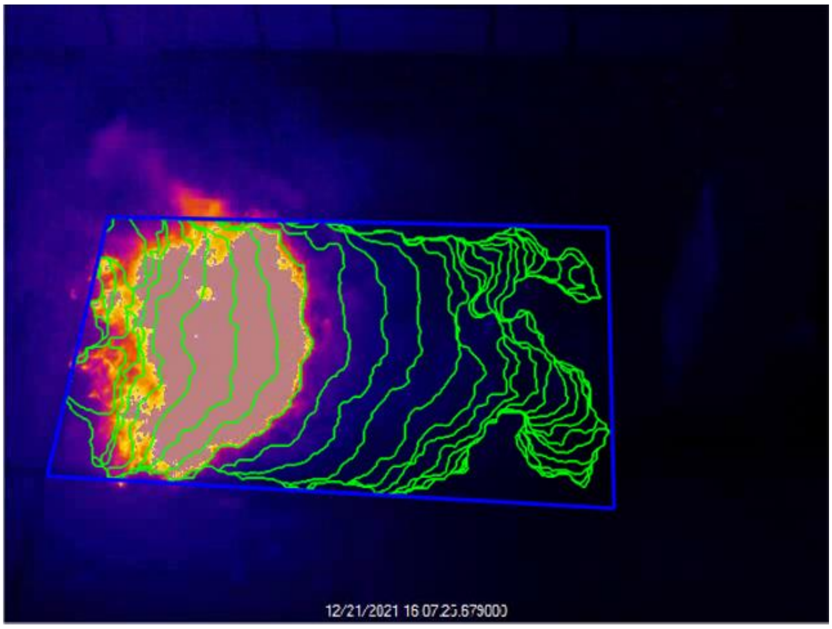

Figure C.2 Image of the rate of spread of the IR camera from Test 1.

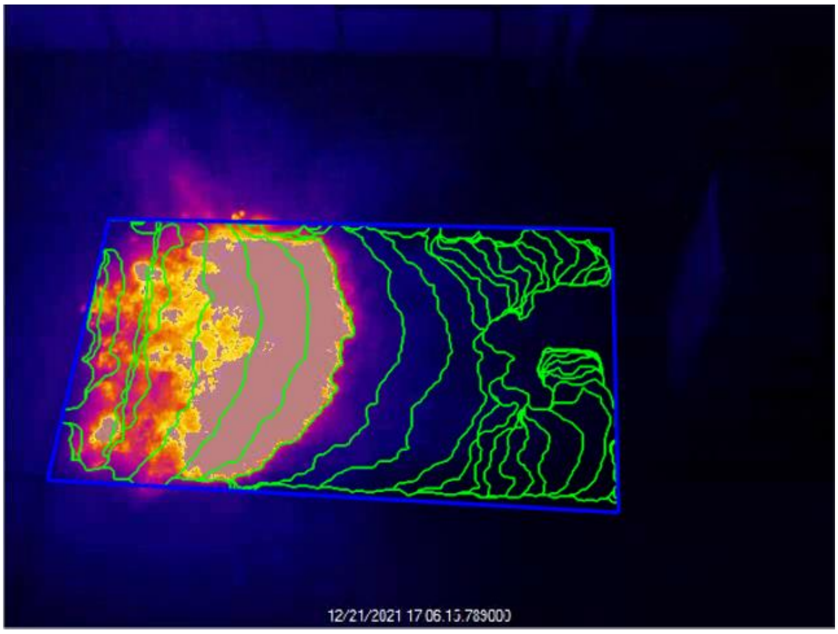

Figure C.3 Image of the rate of spread of the IR camera from Test 2.

Figure C.4 Image of the rate of spread of the IR camera from Test 3.

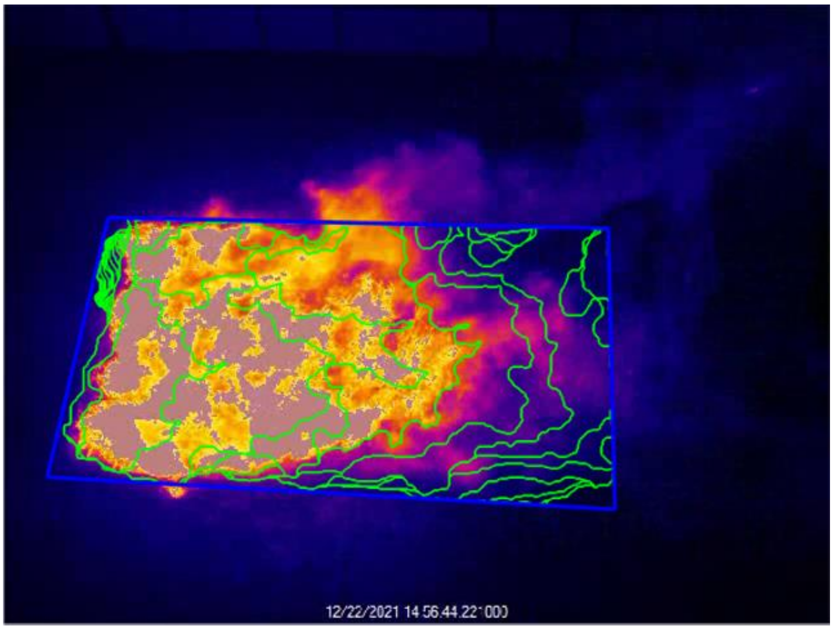

Figure C.5 Image of the rate of spread of the IR camera from Test 4.

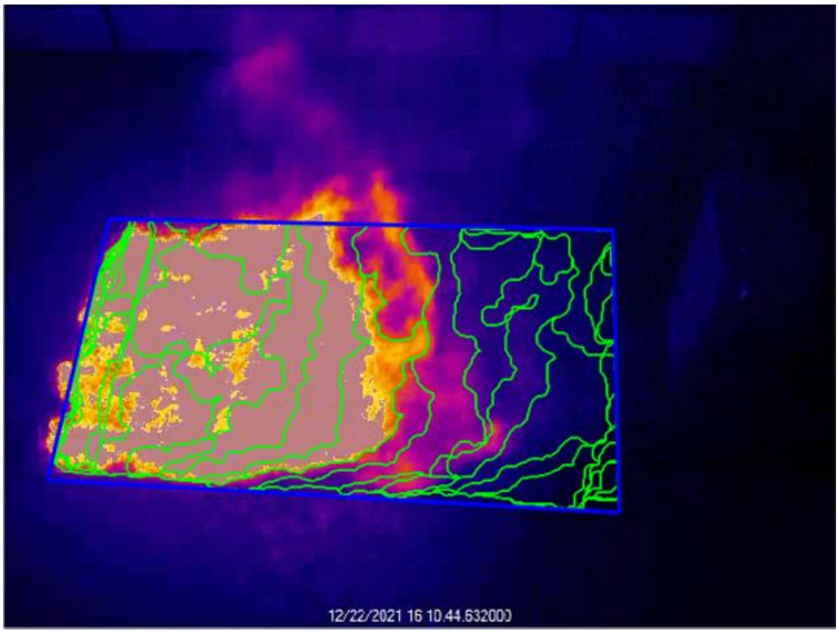

Figure C.6 Image of the rate of spread of the IR camera from Test 5.

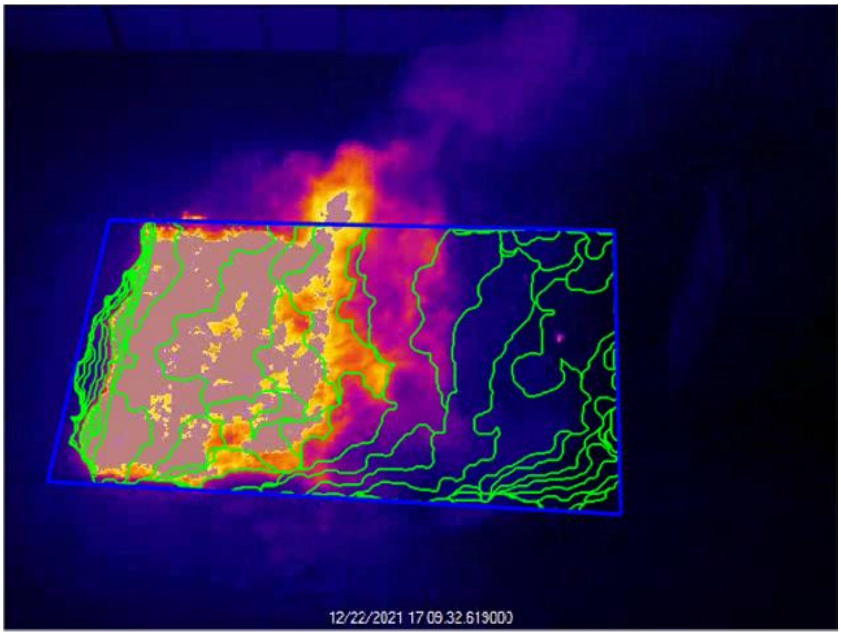

Figure C.7 Image of the rate of spread of the IR camera from Test 6.