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THE EFFECT OF FUEL BED EDGES ON FIRE DYNAMICS IN WIND TUNNEL

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Dissertation within the scope of Master's degree in Mechanical Engineering advised by Professor Doctor Jorge Rafael Nogueira Raposo and by Professor Doctor Luís Carlos Duarte dos Reis and presented to Mechanical Department from Faculty of Sciences and Technology of the University of Coimbra

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The Effect of Fuel Bed Edges on Fire Dynamics in Wind Tunnel

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

Estudo do Efeito de Bordo na Propagação do Fogo no Túnel de Combustão

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"There are two types of people who will tell you that you cannot make a difference in this world: those who are afraid to try and those who are afraid you will succeed."

Ray Goforth

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Abstract

Forest fires are very common in Portugal. It is perhaps the natural disaster that occurs more frequently, being very destructive. Forest fires affect not only forests but also human constructions. This has an economic impact, because we need to expend money to fight forest fires and also to repair the destruction caused by the fire. Forest fires also cause several casualties every year, including human lives, which leads us to study the fire behaviour.

The main objective of the work presented is the study of fire behaviour in the presence or absence of edge wall in order to understand how to replicate the characteristics of a real fire front at laboratory scale.

The study of forest fires is extremely important to understand their behaviour in detail. This way it is possible to give a better response to forest fires in real situations by the firefighting operational in order to keep themselves and populations safe.

The experimental tests were performed at the Combustion Tunnel 3 of the Forest Fire Research Laboratory of the University of Coimbra. The fuel selected was shrub (a mixture of *Erica umbelatta, Erica australis, Ulex minor e Chamaespartium tridentatum*), once it is one of the most common fine fuels in Portuguese forests.

The experimental setup had the objective of testing the influence of two different parameters on the fire propagation such as the presence of the edge walls and the variation of the flow velocity.

As expected, both the increasing of flow velocity and the presence of fuel bed edges led to higher values of rate of spread, fireline intensity, and fire intensity.

Keywords Fire Behaviour, Edge Walls, Laboratory Tests, Fire Spread, Fire Intensity, Forest Fires.

Resumo

Os incêndios florestais são muito comuns em Portugal. São provavelmente os desastres naturais que ocorrem com maior frequência, sendo muito destrutivos. Os incêndios florestais afetam não só a floresta, mas também construções humanas. Isto tem impactos económicos, uma vez que é necessário gastar dinheiro para combater os incêndios e também para reparar os estragos causados por estes. Os incêndios florestais também causam muitas perdas todos os anos, incluindo vidas humanas. Isto leva-nos a estudar o comportamento do fogo.

O objetivo deste trabalho é o estudo da propagação do fogo com e sem paredes laterais de modo a perceber se é possível replicar uma frente de um incêndio florestal real a uma escala laboratorial.

O estudo de incêndios florestais é de extrema importância de modo a entender o seu comportamento de forma detalhada. Desta maneira é possível dar uma melhor resposta no combate aos incêndios florestais, por parte dos operacionais de modo a garantir a sua segurança e das populações.

Os testes experimentais foram realizados no Túnel de Combustão 3, no Laboratório de Estudos sobre Incêndios Florestais (LEIF). O combustível selecionado foi mato (uma mistura de *Erica umbelatta, Erica australis, Ulex minor e Chamaespartium tridentatum*), uma vez que é um dos combustíveis mais comum nas florestas portuguesas.

A metodologia experimental teve como objetivo testar a influência de dois parâmetros distintos para a propagação do fogo, tais como a presença de paredes laterais e a variação da velocidade de escoamento imposto.

Como esperado, tanto o aumento da velocidade de escoamento como a presença de paredes laterais nas extremidades do leito conduziram a maiores valores de velocidade de propagação, de intensidade de frente de chama e de intensidade do fogo.

Palavras-chave: Comportamento do Fogo, Paredes Laterais, Testes Laboratoriais, Propagação do Fogo, Incêndios Florestais, Intensidade do Fogo.

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ε – Emissivity []

σ – Stefan-Boltzmann Constant [W/m^2K^4]

T – Temperature [K]

q_r'' – Radiation heat flow [W/m^2]

q_c'' – Convection heat flow [W/m^2]

h – Heat transfer coefficient [W/m^2K]

R – Rate of Spread [cm/s]

R_0 – Basic Rate of Spread [cm/s]

R' – Nondimensional Rate of Spread []

U – Flow Velocity [m/s]

Ip – Propagation Intensity [MW/m]

H_f – Height of the Flame [cm]

L_f – Length of the Flame

t – Time [s]

θ_f – Tilt of the Flame [°]

β – Angle made by the flame with the horizontal plane [°]

x – Position of the flame along the axis |XX| [cm]

W_f – Fuel load [kg/m^2]

ΔH_f – Heat yield of fuel [MJ/kg]

Acronyms

LEIF – Laboratório de Estudos sobre Incêndios Florestais

DEM – Departamento de Engenharia Mecânica

FCTUC – Faculdade de Ciências e Tecnologia da Universidade de Coimbra

IR – *Infrared Spectrum*

FFDRS – Forest Fire Ganger-Rating System

ROS – Rate of Spread

1. INTRODUCTION

Motivation

The forest fires of 2017 showed that we are not as prepared to give a good response to a disaster as we thought and that there is still a lot to learn about nature and natural disasters, especially forest fires.

Everyday nature challenges the mankind with natural disasters, such as floods, tornados, landslides, thunderstorms, earthquakes, or forest fires not only because of their destructive nature but also because of their dynamic behaviors. In the particular case of forest fires, there are lots of variables that influence their dynamics, such as wind velocity or direction, land slope, type of fuel, humidity, temperature and more. Thus, it is important to study and try to understand how each of these variables can change the fire behavior, this way it is possible to predict and anticipate how the forest fires will act for the different types of conditions and so it is easier to adapt to each different situation and control the fire front.

Each year we are faced with a greater number of forest fires and the loss of lives is becoming more frequent, sometimes because of the fire's big dimensions and sometimes because of our little comprehension of forest fires' behavior. With the climate change came the temperature increase and, consequently, the number of forest fires and their dimensions also increase, so the forest fires became more dangerous.

The massive destruction and casualties caused by the forest fires of 2017 should warn everyone and not only firefighting departments or governments, because sometimes there is not enough manpower to suppress a forest fire and we must adapt to give the best possible response to its dynamics.

The present work focuses on study the dynamics of a fire in presence of fuel bed edges to help us understand if with these edge walls it is possible to represent a fire closer to one in a real situation than without fuel bed edges.

This work was part of the investigation of the Projects FCT, FIRESTORM (PCIF/GFC/0109/2017) and SMOKESTORM (PCIF/MPG/0147/2019). For this projects the fire behavior and the moisture content of the forest fuels are analyzed, taking into account the ongoing climate changes that create more frequent conditions for the occurrence of drought and heat waves that make it easier the incidence of Extreme Wildfire Events (EWE).

It is important to notice that this is the first study involving this type of fuel bed edges and so it is not possible to compare results with other works. This study was proposed by Hoze Solutions GmbH as they believe that fuel bed edges would help us to better represent a forest fire front once the energy released by the fire is contained between the edge walls and this way it is supposed to have a greater fire intensity.

1.1. State of the Art

According to Pinto et al. (2017) it is possible to systematically study the role of numerous factors that influence the creation of fire whirls in forest fires. The same hypothesis is also possible for the numerous factors that influence forest fires propagation.

Using weather data of national stations, it is possible to predict fire outbreaks. (Jurvélius, 2004) says that the Canadian system FFDRS (Forest Fire Ganger-Rating System) is the one that most countries use. With the data obtained by this system it is possible to manage the roles and responsibilities of corporations and landowners to help preventing forest fires.

Britton et al. (1977) found a *"simple and accurate technique of photographically recording rate of fire spread data"* consisting of using black and white infrared film once it is insensitive to smoke and doesn't record it. Therefore, it became possible to photograph flames even through dense smoke. As this technique was only used with photography, a stopwatch was needed to record the interval of time from one shot to the other and this way it became possible to accurately calculate the rate of fire spread.

Randerson et al. (2012) revealed that small fires are responsible for the increase of burned area and global carbon emissions by approximately 35%. This paper shows that small fires are becoming more relevant each year and that the burned area of forest fires is increasing due to the climate changes. Although this increasing of burned area is not directly related to human lives losses, the numbers are worrying.

There are two different forms of fire behaviors classification: the normal fire behavior and the extreme fire behavior (Viegas et al., 2011).

Cheney et al. (2001) identified the implications of the change in the rate of spread resulting from a wind direction. Particularly, when the fire conditions are not extreme the influence of minor changes, such as wind speed or direction, result in dramatic changes in fire behavior.

It is the combination of different variables of long and short term, such as long-term drying of fuel and wind velocity, respectively, and the atmospheric conditions and fire ignition that results in severe fire behavior. According to Sullivan (2004) what differs a severe fire event from others is not the fire dimension or duration, but the value of assets destroyed and the number of people killed.

2. FIRE DYNAMICS

2.1. Definition

Fire Dynamics is *"the field of study that encompasses how fires start, spread, develop, and extinguish."* To characterize fire behavior the better way possible, the interactions of heat transfer and fluid mechanics must be incorporated in fire dynamics (Madrzykowski, 2013).

As it was previously mentioned there are a notorious number of factors that influence fire behavior, and this study has the objective of study the influence of two factors, the wind velocity, and the presence of fuel bed edges at laboratory scale.

The study of fire dynamics is increasingly important in order to predict the fire behavior when in a real situation and this way guarantee the safety of the firefighters and general people, knowing how to fight the fire and when it must be avoided to fight due to its fast spread that makes it impossible to counter and could jeopardize the operational in terrain safety.

With the increasing number of forest fires and the bigger dimensions forest fires are taking, because of climate changes, it is extremely important to understand the fire behavior. The 2017 forest fires are a good example of what we still need to learn about fire behavior to avoid those situations like the ones of Pedrogão Grande, June, and October complex of fires.

This study focuses on fire propagation, so it is possible to predict how a fire front spreads for different wind speeds, for different configurations of fire fronts, and for the conjugation of these two variables.

2.2. Factors for Fire Spread

There are three main groups of influential factors to fire behavior, these factors make the proposed and scientifically accepted "Wildfire Triangle" (Byram, 1959) Figure 2.1. The mentioned groups are the fuel type, the topography, and weather.

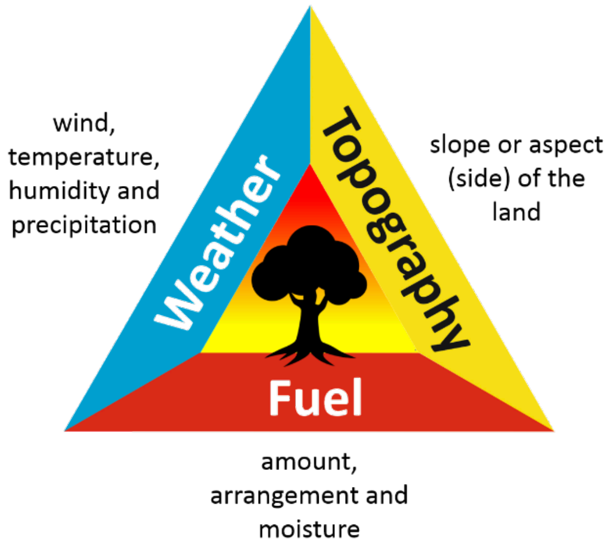


Figure 2.1. Wildfire Triangle (Kern & Krausmann, 2020)

There are many factors that influence the fire behavior, but what really makes it difficult to predict and fully understand the fire behavior is the interaction between those factors and the fire at the same time. Regarding that, it is important to mention that the type of fuel (its amount, arrangement, and moisture) is considered. As the experiments are going to be performed on a horizontal and plane surface, the slope or aspect of the land is not considered. Relatively to the weather, the only factor taken into account is the wind speed and direction induced by the wind-tunnel.

The different characteristics that influence the combustibility of the fuel, such as fuel load, arrangement, moisture, and heat power must be considered. The moisture influence can be attenuated so that the combustibility can be compensated by other meanings as it will be explained later.

The topography is also an important factor that influences the fire behavior and, particularly, its spread. The topographic main characteristics that influence the fire spread are the slope, and the aspect of the land.

Relatively to the weather factors, the most important for forest fires propagation is, evidently, the wind behavior. The wind behavior is very unpredictable, its speed may be different for places next to each other, its direction may change very quickly, and this makes it very hard to characterize and predict its behavior. For a forest fire that extends itself for kilometers, it is not easy to predict its behavior because of the wind velocity and direction that may differ for distinct points of the same fire, additionally the fire also creates its own convective winds, as explained in Viegas (2006).

A very important influential factor of fire behavior is time. According to Viegas (2006) the fire behavior is unstable, once that if the factors previously mentioned are constant over time, the fire presents different propagation characteristics. Therefore, Viegas (2006) proposes a new concept of fire behavior influential factors, adapting the “Wildfire Triangle” to the “Wildfire Square” Figure 2.2.

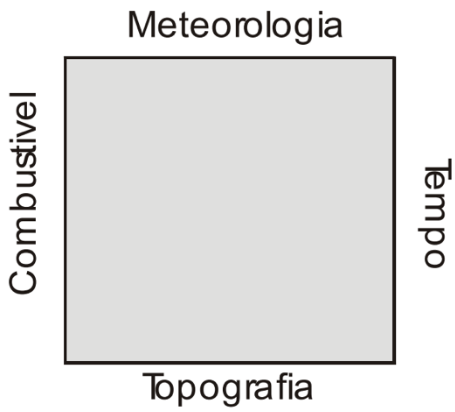


Figure 2.2. Wildfire Square (Viegas, 2006)

2.3. Dynamics of Fire Behaviour

Rodrigues Sampaio (2019) says that fire presents a dynamic behavior once it is directly related with time. Therefore, the fire behavior is the result of the fire interaction with the environment. Furthermore, fire creates convection currents that change the surrounding environment.

When a fire ignites, it spreads with a starting speed. Over time, the fuel bed combustion continues, releasing heat, and inducing ascendent convection currents that result on the appearance of flames and smoke. The vertical convection origins a horizontal current parallel to the fuel bed length and with the same direction of the fire front. Thanks to the horizontal currents created, the rate of spread increases and the oxygen reaches the combustion zone faster. With more oxygen at the fire front, the combustion intensifies, the flames become higher and the rate of spread increases too.

2.4. Heat Transfer Concepts for Forest Fires

Heat transfer is classified in three different mechanisms: conduction, convection, and radiation. During a forest fire, when speaking about heat transmission, the convective and radiative components take values far superior to the conductive ones, this way the component of conduction may be neglected.

The heat released through radiation takes very high numbers, so the study of radiation takes a very important role relatively to heat transmission in forest fires due to its temperature is elevated to the exponent four (Incropera et al., 2011) as it can be observed by the Stefan-Boltzmann Law (**2.1**), where ε is the emissivity, σ represents the Stefan-Boltzmann constant, and T is the absolute temperature.

$$q_r'' = \varepsilon \cdot \sigma \cdot (T - T_s)^4 \tag{2.1}$$

By other hand, the heat released through convection does not reach such high values, but convection represents the fluids movement considering the difference between temperatures for different points of the fluid. The projection of incandescent particles at great distances that can begin secondary fire spots is a consequence of the existence convection currents in conjunction with wind. The convection is represented by the Newton Law (2.2), where the h is the heat transfer coefficient and T_s is the surface temperature.

$$q_c'' = h(T - T_s). \tag{2.2}$$

2.5. Fire Intensity

"Fire intensity is defined as the rate of heat energy released by the fire" (Rossi et al., 2019). More precisely, *"it is defined as the energy per unit volume multiplied by the velocity at which the energy is moving"* (Keeley, 2009) so the resulting vector has the units of [W/m^2] (Rothermel, 1972).

The most useful alternative to the real definition of fire intensity is the Byram's fire intensity, which is currently used as fireline intensity (Rossi et al., 2019).

For this study we are first going to use the fireline intensity equation (2.3) (Byram, 1959) to first determine the intensity of the fire, for the center point of the fire front profile, where R is the rate of spread, ΔH_f is heat yield of the fuel (in this case $\Delta H_f = 20$ MJ/kg), and W_f is the fuel load.

$$I_p = R \cdot \Delta H_f \cdot W_f \tag{2.3}$$

To have a better understanding of the fire behavior when the two configurations (with and without fuel bed edges) are compared, we must resort to the fire intensity equation (2.4) (Weise & Biging, 1996), where L_f is the flame length.

$$I_B = \left(\frac{L_f}{0.0775}\right)^{\frac{1}{0.46}} \tag{2.4}$$

When we use fuel bed edges, the fire generates the "*trench effect*". The "*trench effect"* is generated by the interaction of flames with entrained air under the particular condition of not having air flow coming from the laterals of the fire. This gives an idea of infinite extension of across the full width of a tread (Smith, 1992).

3. METHODOLOGY – EXPERIMENTAL TESTS

To better understand the fire dynamics in a real situation, we made some experimental tests at the laboratory. The possibility of watch how the fire behaves in a laboratorial scale helps us to have a better perspective of what happens in a real forest fire.

For this study we used the Combustion Tunnel 3 (wind-combustion tunnel) that is at the LEIF facilities. This tunnel has the following dimensions: a length of 8 m, a width of 6 meters and two side walls with a height of 2 meters (one of these walls is made of glass so we can have three different perspectives of the fire in total – top, front and side view).

The tunnel is also equipped with two fans with 35 kW, each, and capable of producing a flow velocity of 8 m/s.

For the present study, there were used flow velocities of 0, 1 and 3 m/s for a better understanding of the fire behavior, once there was no need of using a higher speed flow velocities because of the use of edge walls, which means that these flow velocities were used with and without the edge walls.

The material selected for the edge walls was an autoclaved cellular concrete (Ytong) composed by quartz sand, air, water, lime, cement, and aluminum powder and presents the following properties: fire resistance (up to 3 hours), lightweight material (75% lighter than traditional concrete) and durable (normal weather conditions won't degrade this material). This material was selected because as the fuel bed it has porosity offering a path for the fire to progress.

The different configurations of each experimental test performed for this study are presented at the Table 3.1

Table 3.1. Experimental Tests Parameters

Reference	Flow Velocity U [m/s]	Fuel Bed Edges [Yes/No]	Moisture Content [%]	Load [kg/m^2]	R_0 [cm/s]	Fuel Bed [m^2]
Experiment 1	0	No	11.8	1.5	1.009	16
Experiment 2	1	No	10.6			
Experiment 3	3	No	12.7			
Experiment 4	0	Yes	12.4			
Experiment 5	1	Yes	12.1			
Experiment 6	3	Yes	12.6			

For each experiment three tests were performed, except for the experiments 1 and 4 once the flow velocity was 0 for both cases and for these experiments two tests were enough to obtain sufficient data.

3.1. Configuration

For the experimental tests, the geometry of the fuel bed was a 4m x 4m square. This configuration was fixed to all the experiments, this way we guarantee the geometry and dimension of the fuel bed won't interfere with the obtained results for each experiment, therefore the different results from each experiment will mainly depend on the flow velocity and on the presence or absence of fuel bed edges. The fuel bed configuration is represented in the Figure 3.1 with the letters A, B and C representing the fuel bed, the wind tunnel fans and the cameras, respectively.

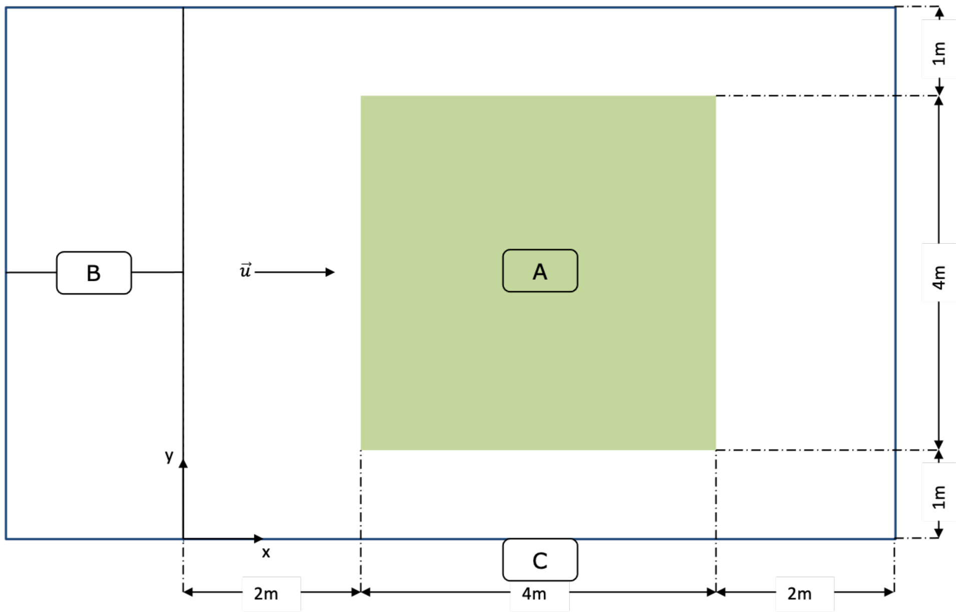


Figure 3.1. Fuel Bed Configuration

3.1.1. Fuel Load

Every fuel has a certain amount of humidity. This humidity varies with different weather factors, such as humidity of the air or temperature, consequently it will depend on the time of the day. This way we must calculate the exact percentage of humidity that is present in the fuel and so we can substitute the water mass by the respective quantity of cellulose.

To do that we first need to determine the percentage of humidity present in the dry base and then calculate the total fuel load for the wet base following the equation (**3.1**).

$$Fuel\ Load = Specific\ Load\ \times \left(1 + \frac{Humidity}{100 - Humidity}\right) \times Fuel\ Bed\ Area\ . \tag{3.1}$$

The fuel used to perform the experiments had a specific load of fuel 1.5 kg/m^2 with a uniform distribution for the 16 m^2 fuel bed (Raposo, 2016).

3.1.2. Ignition

To ignite the fire, we used a cotton yarn soaked in gasoline and diesel laid at all the width of the fuel bed edge closer to the fans and perpendicularly to the direction of the flow velocity and fire spread. This way we have a line ignition which produces a fire closer to the reality. As we only used one cotton yarn for each test, the ignition could be made by one person, and this way it is easier to start all the experiments the same way, and so the fire dynamics won't differ from one another because of the ignition.

3.1.3. Fuel Bed Edges

The fuel bed edges were added for the experiments 4, 5 and 6 as a new factor that influences the fire dynamics. These walls were added with the intent of analyzing the fire intensity, the geometry of the flame and the rate of spread and then compare the data from these experiments with the data from the experiments without the fuel bed edges. The configuration of the experiments is represented in the Figure 3.2 where the letters represent the same elements of the Figure 3.1.

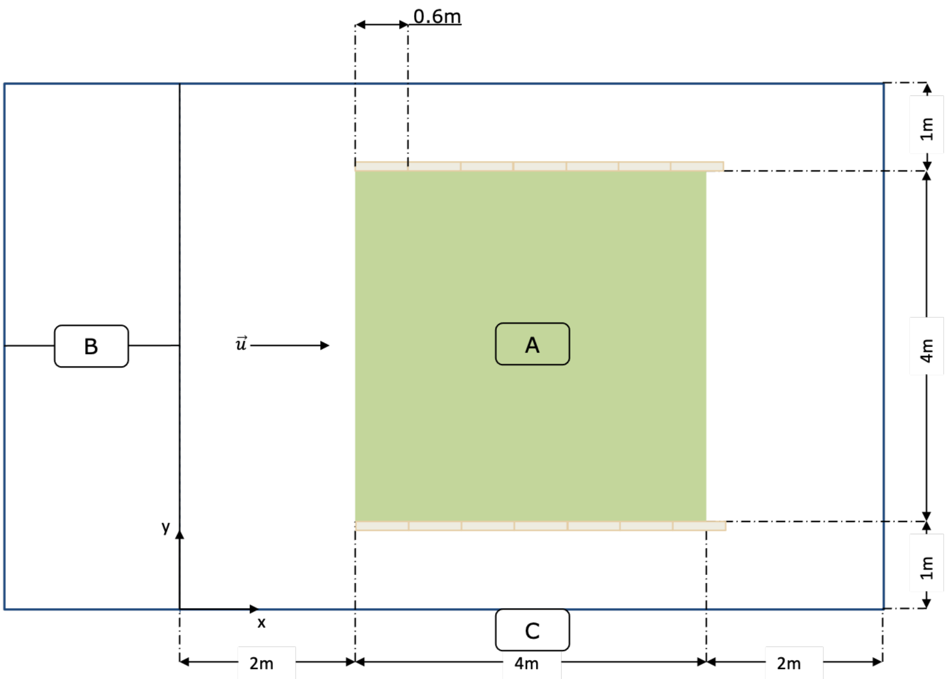


Figure 3.2. Fuel Bed Configuration with Fuel Bed Edges

3.2. Rate of Spread

In terms of study of fire dynamics and behaviour, the rate of spread (ROS) is one of the most important properties.

For the calculation of ROS, we used the images taken by the IR camera, but as the camera only records video we had to resort to a software called *Video to JPG Converter* to extract the frames needed for the analysis. For each flow velocity frames were collected for different intervals of time once there were tests that took longer than others, so for a flow velocity of 0 m/s, 1 m/s and 3 m/s, it was defined an interval between frames of 20s, 10s and 5s, respectively. This way almost the same number of frames for each experiment was collected.

After the frame extraction it was drawn the front fire profile for each frame of every experiment and, using *Microsoft Office* ® tools, it was possible to measure the distances covered for each instant of time and this way calculate the ROS.

The ROS is determined using the position of the fire front over time, this means that for an instant of time the position of the fire front is marked and, after marking all the positions for each instant, we determine the ROS using the equation (**3**.**2**).

$$R_i = \frac{x_i - x_{i-1}}{t_i - t_{i-1}}. \tag{3.2}$$

3.2.1. Basic Rate of Spread (R_0)

According to Viegas (2005) the fuel bed combustibility is defined by the greater or lesser difficulty this one has to support the spread of the fire front.

The basic rate of spread (R_0) is the rate of spread obtained for basic conditions, such as horizontal fuel bed, linear front of flames, absence of wind (flow velocity = 0 m/s) and the width of the fuel bed must be a lot bigger than the height of the flames, this way there is no interference of other factors that could influence the fire dynamics.

As our experiment 1 was performed under these conditions we used this one to obtain our R_0.

To minimize the variation of the properties of the fuel bed, we reduce the rate of spread to nondimensional values (Viegas & Neto, 1991). Therefore, the nondimensional rate of spread (R') is obtained using the R_0. As the equation (3.3) shows.

$$R' = \frac{R}{R_0} \tag{3.3}$$

3.2.1. IR Camera

As previously mentioned, the captured images to analyze the ROS were taken with resort to an infrared camera. The camera that we used was a FLIR ThermaCam SC660.

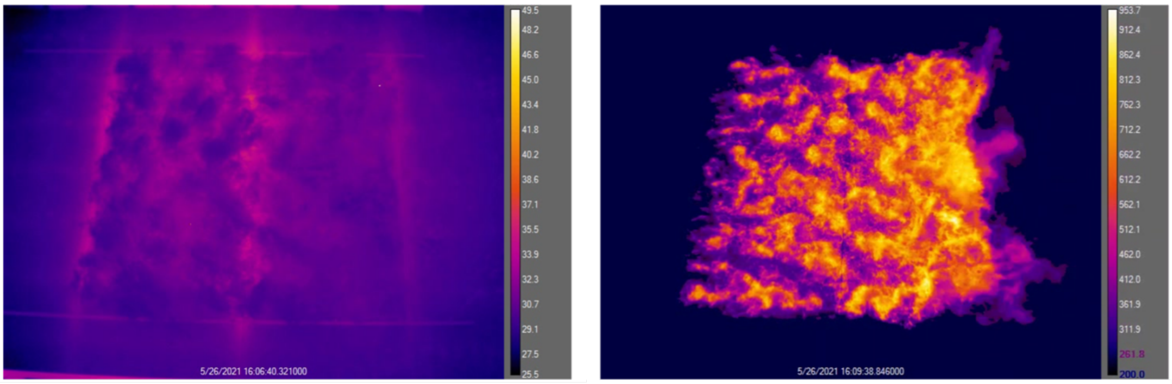
The camera was positioned so that it could capture the entire fuel bed, to achieve this position we used a lifting platform so the camera could be high enough as it can be seen in the Figure 3.3.

Figure 3.3. Image of the Fuel Bed and the Lifting Platform

For this study, we used two spectrums of temperatures, one between the interval [-40;120°C] so we could take images of the fuel bed before the ignition and another between the interval [300°C;1500°C] so we could see the spread of the fire once the temperatures achieved during the tests are extremely high. The different spectrums can be seen in the Figure 3.4.

To ensure a reasonable accuracy of all measurements there were used three cameras (two visual and one infrared), the infrared and one of the visual cameras were placed on the lifting platform to record all the fuel bed, and the other camera was placed laterally to record another view as suggested by (Domingos X. Viegas et al., 2006).

To guarantee that the measurements would be correct, the camera was placed in an orthogonal position to the fuel bed plane and the corrections to the distortion caused by the lens were properly made.



a) b)

Figure 3.4. IR images for the Temperature Interval of: a) [-40°C;120°C]; b) [300°C;1500°C]

3.3. Flame Geometry

The flame geometry is a very important component of a fire. It is the flame geometry that permits us to determine the intensity of the fire instead of only determine the fireline intensity. The flame geometry is divided by three main parameters, these are the height of the flame, the tilt of the flame, ant the length of the flame.

The height and the tilt of the flame are measured using images from the side camera, place on the floor and perpendicular to the fire propagation line. For the images recording we used a Sony FDR-AX100E camera.

After capturing the images, the same steps as the ones mentioned to determine the rate of spread were made. So, we used the *Video to JPG Converter* software to extract the frames needed for the analysis. As previously mentioned, the videos for slower flow velocities last longer, so for a flow velocity of 0 m/s, 1 m/s and 3 m/s, it was defined an interval between frames of 20s, 10s and 5s, respectively, in order to have approximately the same number of frames for each experimental test.

After the frames' extraction the height and the tilt of the flames were measured, using each frame, with resort to *Microsoft Office* ® tools.

An example of a lateral image of the fire in the wind tunnel is illustrated in Figure 3.5.

Figure 3.5. Lateral Image of the Fire in the Wind Tunnel

After all the measurements related to the height and the tilt of the flames were made, it was possible to determine the flame length. The flame geometry is represented in Figure 3.6.

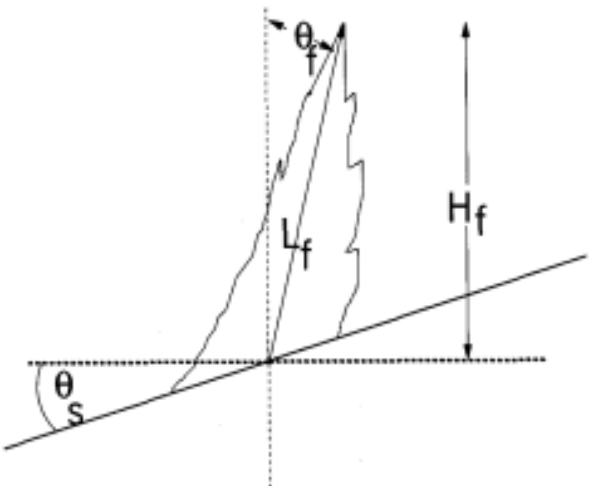


Figure 3.6. Representation of the Flame Geometry (adapted from (Weise & Biging, 1996))

As we can observe in the figure above, it is possible to determine the length of the flame using trigonometry. So, for this calculation, the equation (**3.4**) was used.

$$L_f = \frac{H_f}{\cos \theta_f} \tag{3.4}$$

After the determination of the length of the flames for each experimental test, it was possible to determine the fire intensity, once this one depends on the flame length.

4. RESULTS ANALYSIS AND DISCUSSION

The main data obtained from the experimental tests were the rate of spread, R [cm/s], measured through the infrared images, the height of the flames, H_f, and the tilt of the flames, θ_f, measured through visual images from the side camera. The fire intensity and length of the flame results were obtained using the rate of fire, and the height and tilt of the flames, respectively.

There are two groups dividing this analysis according to the studied parameter. These two groups are the wind velocity U (0, 1, and 3 m/s), and the presence or absence of fuel bed edges.

4.1. Experimental Typology – Without Fuel Bed Edges

The configuration of these experiments is presented in Figure 4.1.. The wind direction, and velocity, and the propagation analysis is performed according to the referential represented in Figure 4.1.

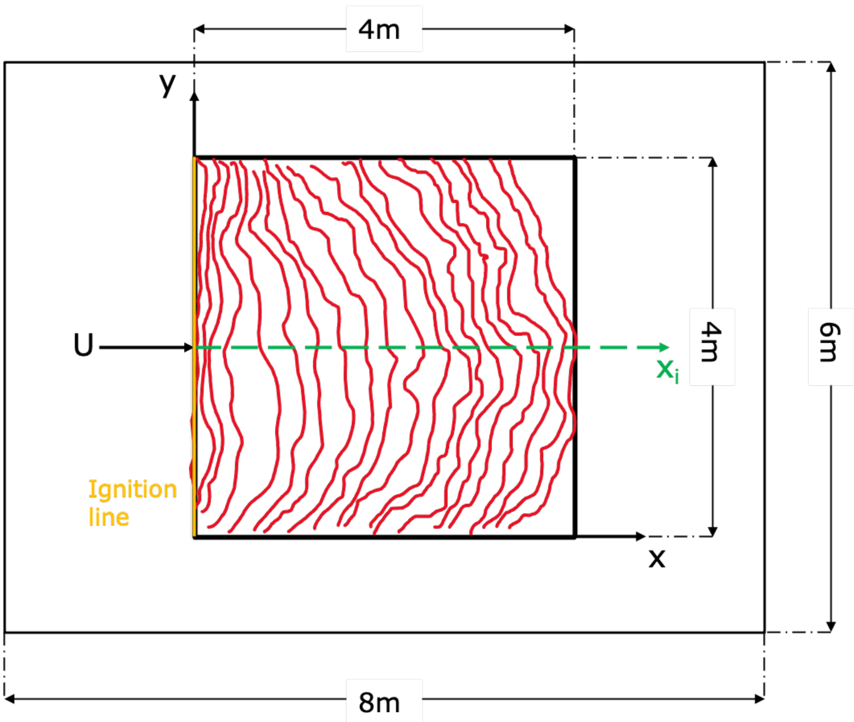


Figure 4.1. Direction of the propagation and Flow Velocity without Fuel Bed Edges

4.1.1. Analysis of Rate of Spread for Different Flow Velocities

In this section, it was analyzed the rate of spread for the different flow velocities used to perform the experimental tests without fuel bed edges.

We can compare the experiments 1, 2, and 3, to analyze the influence of flow velocity on the rate of spread. This can be observed in Figure 4.2.

For this analysis the rate of spread values of all experimental tests were compilated and divided by the different flow velocities they were performed for (0,1 and 3m/s). The graphic series, R'_1, R'_2 and R'_3, correspond to the average values of rate of spread of each experiment, respectively.

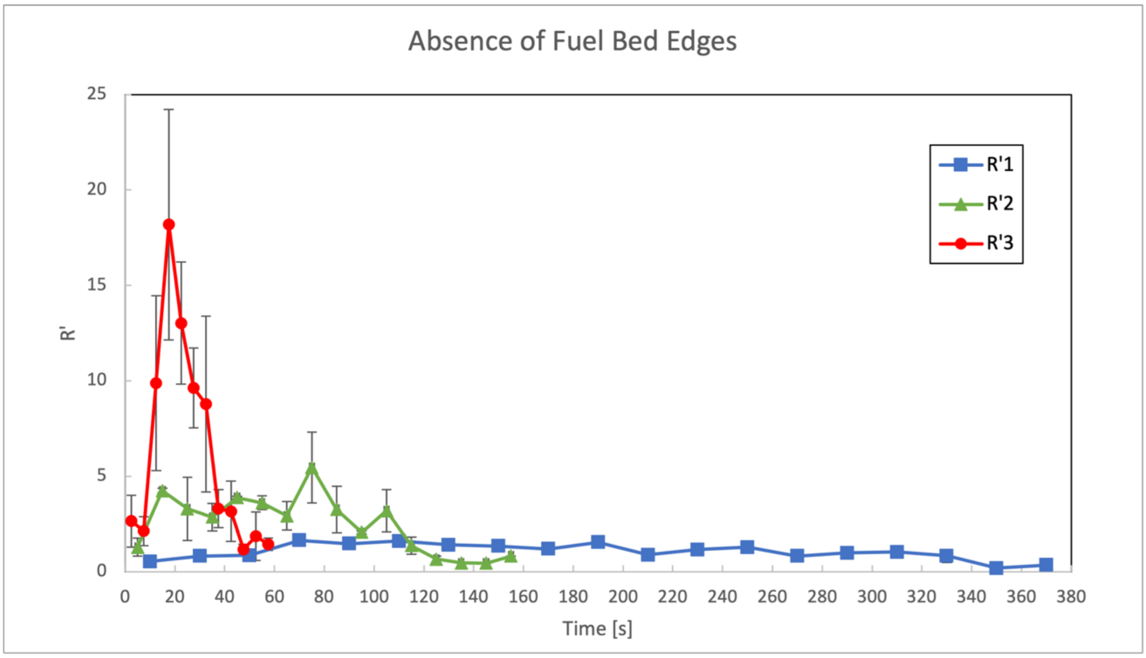


Figure 4.2. Representation of the Different Rates of Spread Without Fuel Bed Edges

As we can observe on the figure above, the influence of flow velocity on the rate of spread is greater the higher its values. In the figure when the flow velocity is increased, the rate of spread also increases, but the measurement error associated with higher flow velocity also increases.

This matches the hypothesis that says the rate of spread has a significantly increase when the wind direction is the same as the propagation of the fire (Viegas, 2006).

We can also notice that the rate of spread has many fluctuations for a fuel bed without fuel bed edges, as it presents very different values from one instant to another for the same flow velocity.

As the rate of spread increases, we can observe that the time of each experiment decreases, as it was expected.

What also can be noted is that the maximum values of the ROS are generated earlier for higher values of flow velocity. That is, the maximum value of the ROS for a flow velocity of 3 m/s is 18.19 and it happens at 17.5 seconds and then it has an abrupt decrease, while for a flow velocity of 1 m/s the maximum value of the ROS happens at 75 seconds with a value of 5.46 and decreases slower than the curve of 3 m/s flow velocity. The curve for a 0 m/s flow velocity has a too small variation to be analyzed when compared to the other ones.

4.1.2. Analysis of Fireline Intensity for Different Flow Velocities

In this section, after obtaining the rate of spread it is possible to determine the fire intensity, as it was previously mentioned on equation (**2.3**). As the fire intensity, or fireline intensity, to be more precise, is directly related to the rate of spread, it is expected to present the same graphic layout in Figure 4.3.

For this analysis the fireline intensities of all experimental tests were compilated and divided by the different flow velocities they were performed for (0,1 and 3m/s). The graphic series, I_{p1}, I_{p2}, and I_{p3} correspond to the average values of fireline intensity of each experiment, respectively.

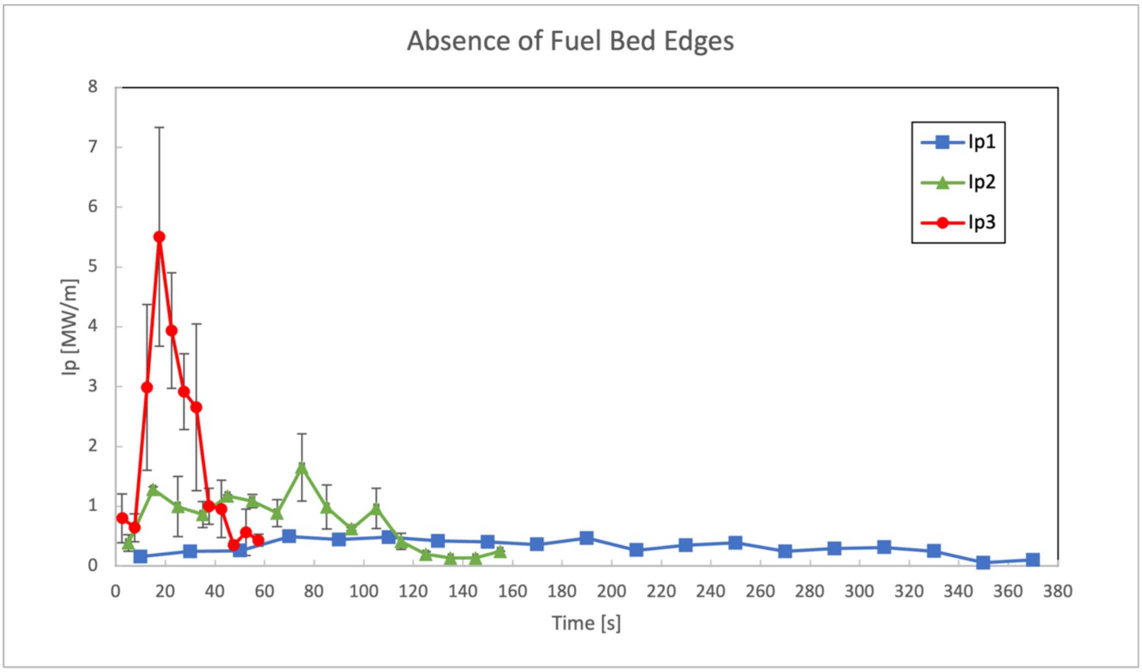


Figure 4.3. Representation of the Different Fireline Intensity Values Without Fuel Bed Edges

As we can observe, the fireline intensity values present the same curve layout of the rate of spread ones, as it was expected once fire intensity depends on the rate of spread.

Another thing that can be noticed is that the measurement error associated with higher flow velocities increases just like the rate of spread one.

This proves that fireline intensity increases when the flow velocity increases as long as the wind direction is the same as the spread of the fire.

4.1.3. Analysis of Flame Height for Different Flow Velocities

In this section, the height of the flames can be observed. The height of the flame is an important component of a fire, since it is possible to calculate the flame length using the values of the height of the flame and the tilt of the flame as it is going to be explained later.

The representation of the height of the flame for each flow velocity can be observed in the Figure 4.4.

It is important to notice that for this analysis the flame heights of all experimental tests were compiled and divided by the different flow velocities they were performed for

(0,1 and 3m/s). The graphic series, H_{f1}, H_{f2}, and H_{f3} correspond to the average values of flame height of each experiment, respectively.

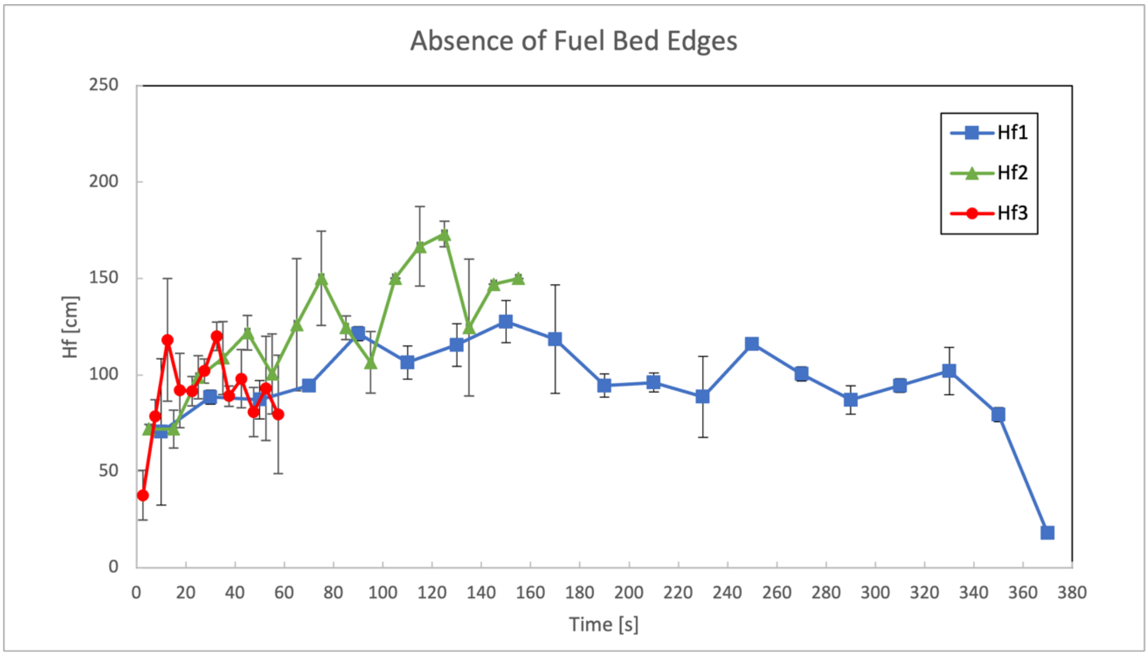


Figure 4.4. Representation of the Different Heights of Flame without Fuel Bed Edges.

The figure shows an interesting fact, as we can observe the height of the flames for a flow velocity of 0m/s has very small variations when compared with the ones for flow velocities greater than 0.

Other observation that can be made is that the height of the flame for 3m/s cannot be as high as the one for 1m/s because the fire reaches the end of the fuel bed much faster, so the flames stop to grow when there is no more fuel to burn.

4.1.4. Analysis of Flame Tilt for Different Flow Velocities

In this section, it was analyzed the tilt of the flame. The tilt of the flame is the angle that the flame makes with the vertical axis, as it can be observed at Figure 3.6.

This value must be obtained so it is possible to calculate the flame length. These values, as the values of the flame height were obtained through lateral images of the fire.

The graphic in the Figure 4.5 is the result of the side images measurements, as it was mentioned in the section 3.1.

Notice that the flame tilts of all experimental tests were compiled and divided by the different flow velocities they were performed for (0,1 and 3m/s) for this analysis. The graphic series, θ_{f1}, θ_{f2}, and θ_{f3} correspond to the average values of the flame tilt of each experiment, respectively.

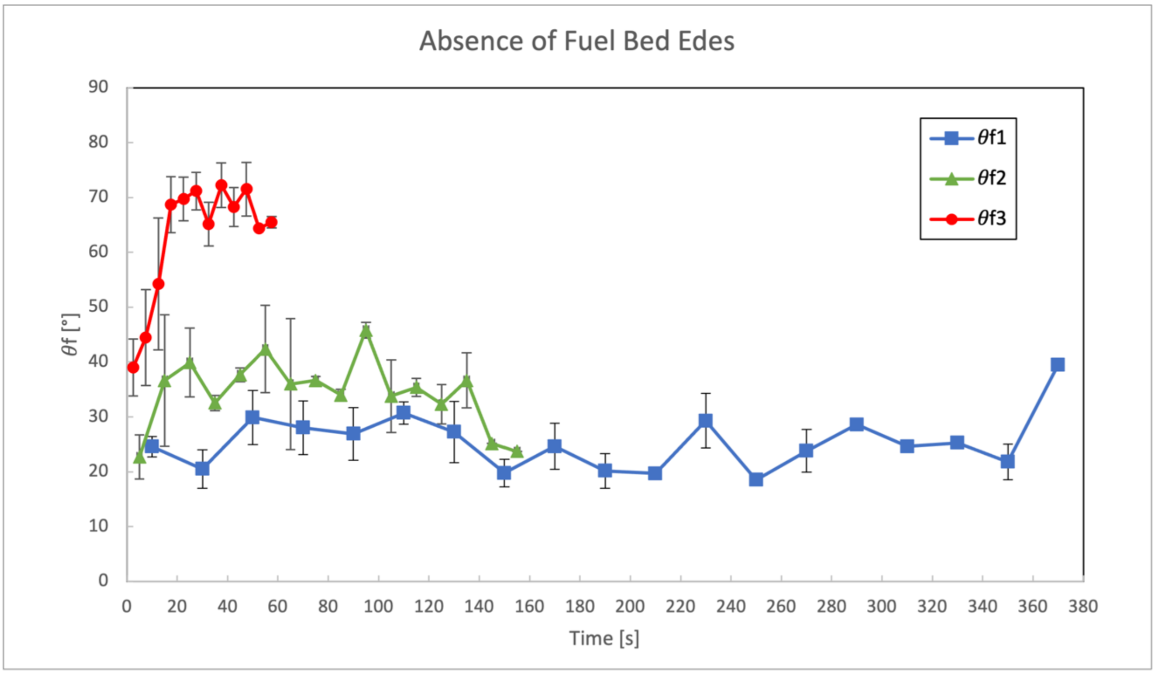


Figure 4.5. Representation of the Different Flame Tilt Without Fuel Bed Edges

With the observation of the chart, we can notice that the tilt of the flame increases for higher flow velocities. We can also notice that without wind the tilt of the flame is almost constant, showing that when these is no flow, the flames have an almost vertical profile.

Following these results, it is expected to have very different values of flame length for the different flow velocities.

4.1.5. Analysis of Flame Length for Different Flow Velocities

Here we can observe the different flame lengths once we already obtained the values of flame height and flame tilt, we can now calculate the flame length using trigonometry (3.4).

With the flame length values calculated, we can now observe the results at Figure 4.6.

Notice that the flame length values of all experimental tests were compilated and divided by the different flow velocities they were performed for (0,1 and 3m/s) for this analysis. The graphic series, L_{f1}, L_{f2}, and L_{f3} correspond to the average values of the flame length of each experiment, respectively.

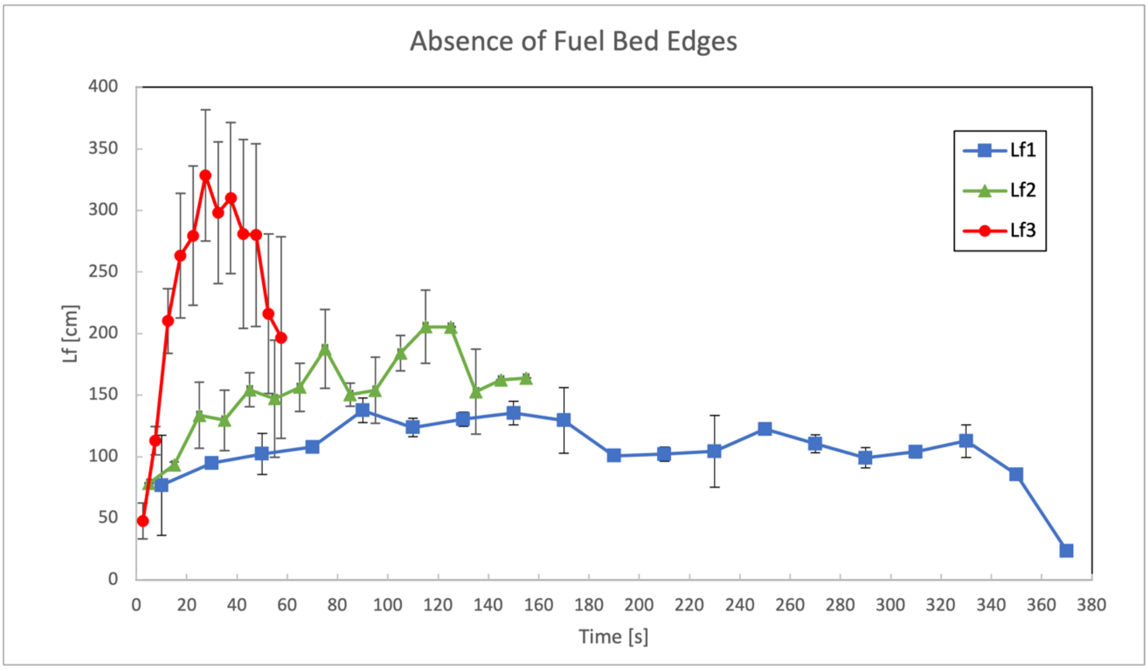


Figure 4.6. Representation of the Different Flame Length Without Fuel Bed Edges

We can notice that, as expected, the length of the flame is higher for higher flow velocities. This matches the rate of spread and fire intensity analyses, helping us conclude that faster wind speeds generate higher values of rate of spread and flame length, and, consequently, higher values of fireline and fire intensity.

4.1.6. Analysis of Fire Intensity for Different Flow Velocities

In this section, we can observe the fire intensity values thanks to the already determined length of the flame. The fire intensity was determined with resort to the equation (2.4).

The obtained fire intensity values can be analyzed using the Figure 4.7.

For this analysis the fire intensity values of all experimental tests were compilated and divided by the different flow velocities they were performed for (0,1 and 3m/s). The graphic series, I_{b1}, I_{b2} and I_{b3}, correspond to the average values of fire intensity of each experiment, respectively.

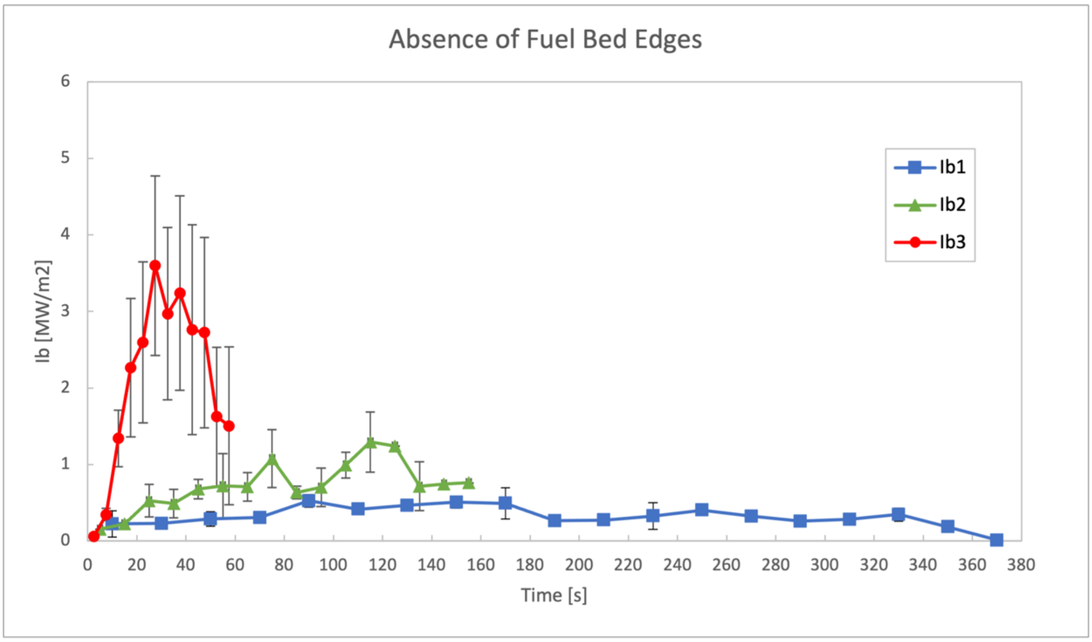


Figure 4.7. Representation of the Different Fire Intensities Without Fuel Bed Edges

Comparing the fire intensity with the fireline intensity we can observe that the maximum value of intensity is higher for the fireline, but when we compare de sum of all the intensity values are higher for this fire intensity. These comparation is only noticed for a flow velocity higher than 0 m/s.

To have an easier perception of these observation, the referred values are compilated in the Table 4.1.

Table 4.1. Comparation Between Fireline and Fire Intensity without Fuel Bed Edges

Experiment	Fireline Intensity [MW/m]		Fire Intensity [MW/m^2]	
	Maximum Value	Sum	Maximum Value	Sum
1	0.49	6.00	0.53	6.14
2	1.65	12.02	1.29	12.13
3	5.50	22.74	3.60	25.04

4.2. Experimental Typology – With Fuel Bed Edges

The configuration of this experiment changes just for the fact that fuel bed edges were added, but the fuel bed area, the direction the wind velocity, and rate of spread were measured were the same as the ones represented in Figure 4.1. The new configuration can be seen in Figure 4.8. Notice that the fuel bed edges extend beyond the fuel bed to guarantee that the conditions are the same at every point of the fuel bed.

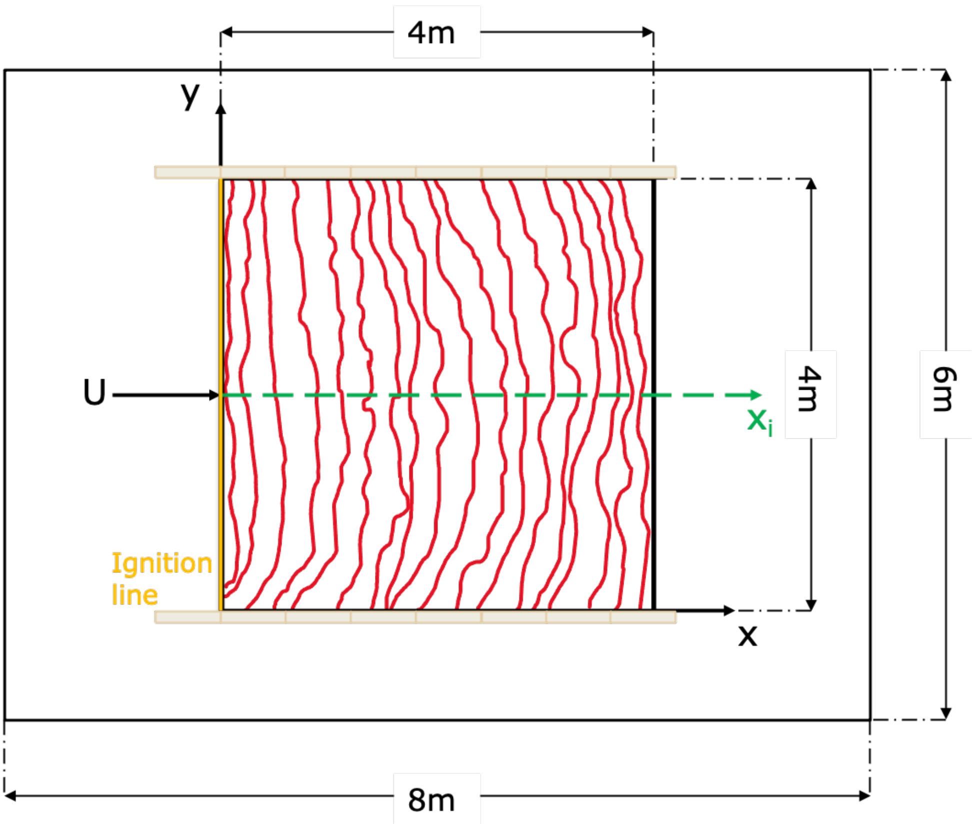


Figure 4.8. Direction and way of the ROS and Flow Velocity with Fuel Bed Edges

For this section we are going to analyze the same aspects of the section 4.1. and after that we are going to proceed to the comparison between the two different configurations of the fuel bed. This way it is possible to observe if the fuel bed edges help to represent a more reliable fire front when compared with experiments without fuel bed edges.

4.2.1. Analysis of Rate of Spread for Different Flow Velocities

In this section, we can compare the experiments 4, 5, and 6, to analyze the influence of flow velocity on the rate of spread. The Figure 4.9 illustrates the rate of spread results for the three different flow velocities.

For this analysis the rate of spread values of all experimental tests were compiled and divided by the different flow velocities they were performed for (0,1 and 3m/s). The graphic series, R'_4, R'_5 and R'_6, correspond to the average values of rate of spread of each experiment, respectively. Notice that these experimental tests have already been performed with fuel bed edges.

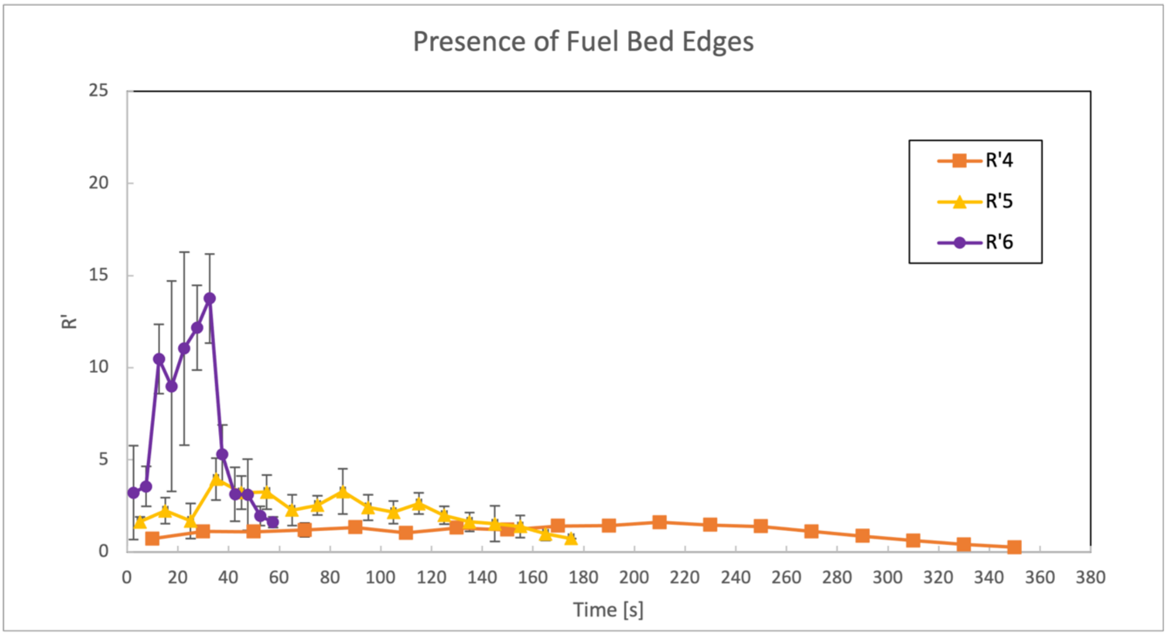


Figure 4.9. Representation of the Different Rates of Spread with Fuel Bed Edges

The influence of flow velocity on the rate of spread continues to be notorious. What we can notice is that the difference between the rate of spread of each experiment is not as discrepant as the ones without fuel bed edges.

The graphic also continues to show that for flow velocities different from 0 m/s the rate of spread reaches its maximum value at the middle of the path, but the rate of spread appears to oscillate less than when there are no fuel bed edges. This is going to be analyzed in the section 4.3.

4.2.2. Analysis of Fireline Intensity for Different Flow Velocities

With the values for the rate of spread measured, the fire intensity can now be determined as previously mentioned by the equation (**2.3**) and then presented in the Figure 4.10.

For this analysis the fireline intensities of all experimental tests were compilated and divided by the different flow velocities they were performed for (0,1 and 3m/s). The graphic series, I_{p4}, I_{p5}, and I_{p6} correspond to the average values of fireline intensity of each experiment, respectively. Notice that these experimental tests have already been performed with fuel bed edges.

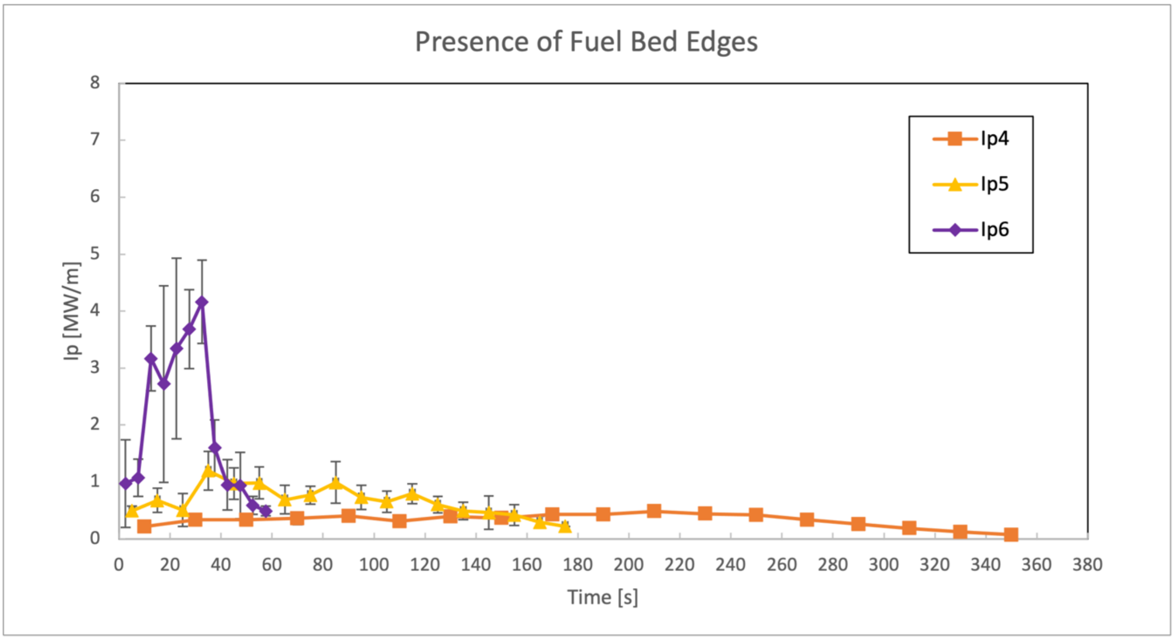


Figure 4.10. Representation of the Different Fire Intensity Values with Fuel Bed Edges

As the fireline intensity is calculated with resort to the rate of spread, as expected, the presented layout is the same as the one in Figure 4.9.

When observing the fireline intensity values, it is possible to notice that the maximum value for each experimental test with fuel bed edges is smaller than the maximum value of the fireline intensity when there is no fuel bed edges.

Despite the experimental tests present higher maximum values when performed without fuel bed edges, the sum of the fireline intensity values presents higher values for the experimental tests performed with fuel bed edges.

4.2.3. Analysis of Flame Height for Different Flow Velocities

In this section, it is possible to observe the flame height values that were measured using the images of the side camera placed on the floor.

The results of the flame height measurements can be observed in the Figure 4.11 above.

It is important to notice that for this analysis the flame heights of all experimental tests were compilated and divided by the different flow velocities they were performed for (0,1 and 3m/s). The graphic series, H_{f4}, H_{f5}, and H_{f6} correspond to the average values of flame height of each experiment, respectively.

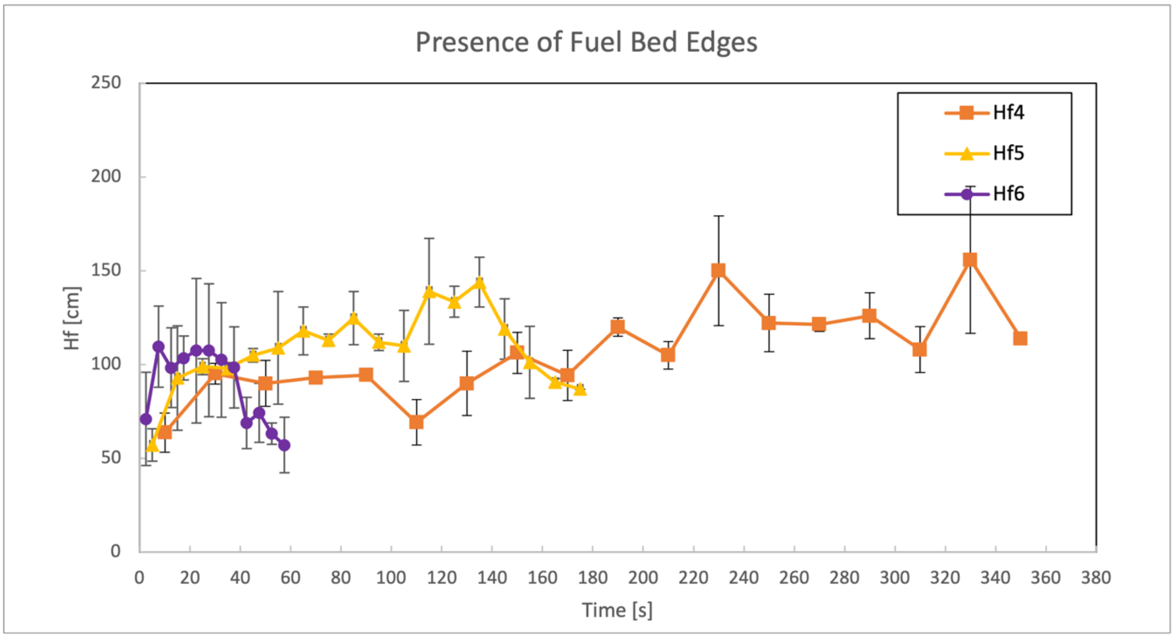


Figure 4.11. Representation of the Different Heights of Flame with Fuel Bed Edges

We can notice that the height of the flames presents very similar values for the different flow velocities when in the presence of fuel bed edges. This shows that the that the flame height is more constant when we use fuel bed edges. This means that if, as expected, the flame tilt values are higher for higher flow velocities, as we observed in the experimental tests without fuel bed edges, the flame length is going to be greater for faster wind speeds.

4.2.4. Analysis of Flame Tilt for Different Flow Velocities

In this section, the tilt of the flame can be analyzed. The tilt of the flame, as previously mentioned, is the angle that the flame makes with the vertical axis, as it can be observed at Figure 3.6.

This value must be obtained so it is possible to determine the flame length.

The graphic in the Figure 4.12 is the result of the side images measurements, as it was mentioned in the section 3.1.

Notice that the flame tilts of all experimental tests were compiled and divided by the different flow velocities they were performed for (0,1 and 3m/s) for this analysis. The graphic series, θ_{f4}, θ_{f5}, and θ_{f6} correspond to the average values of the flame tilt of each experiment, respectively.

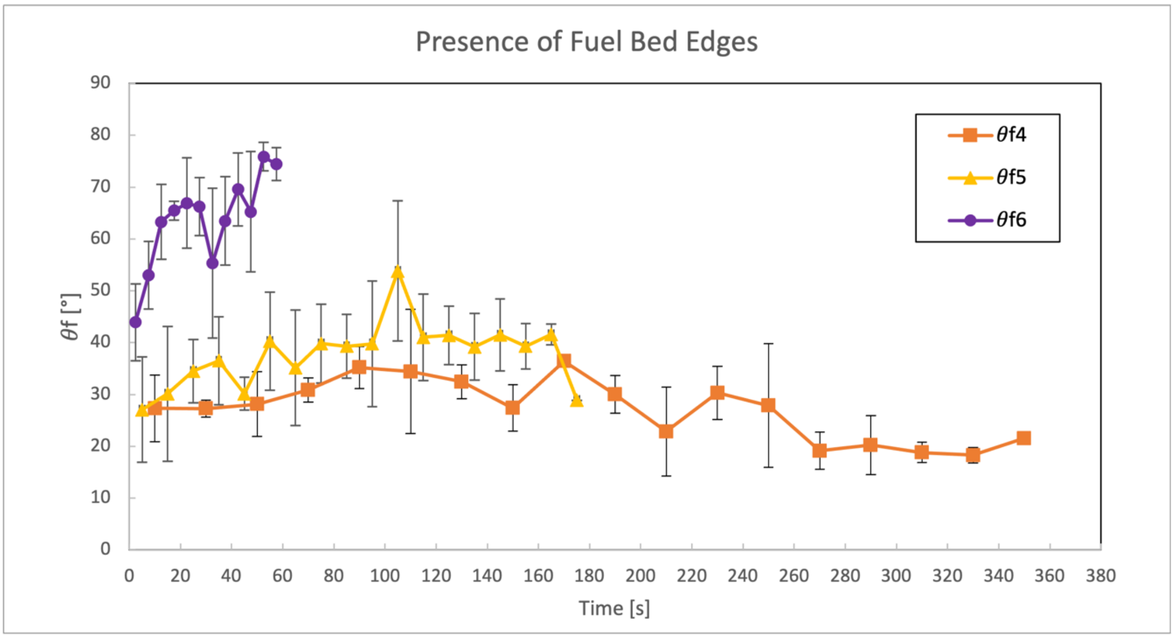


Figure 4.12. Representation of the Different Tilts of Flame with Fuel Bed Edges

This figure confirms what it was previously mentioned about the flame tilt, showing that for higher flow velocities, the flames present a greater slope.

So, if the flame length hypothesis is correct, then the difference between the values of the length of the flame is greater as greater is the flow velocity.

4.2.5. Analysis of Flame Length for Different Flow Velocities

In this section, we can observe the different flame lengths once we already obtained the values of flame height and flame tilt, it is possible to proceed the same way as it was in the section 4.1.5.

With the flame length values calculated, we can now observe the results at Figure 4.13.

Notice that the flame length values of all experimental tests were compilated and divided by the different flow velocities they were performed for (0,1 and 3m/s) for this analysis. The graphic series, L_{f4}, L_{f5}, and L_{f6} correspond to the average values of the flame length of each experiment, respectively.

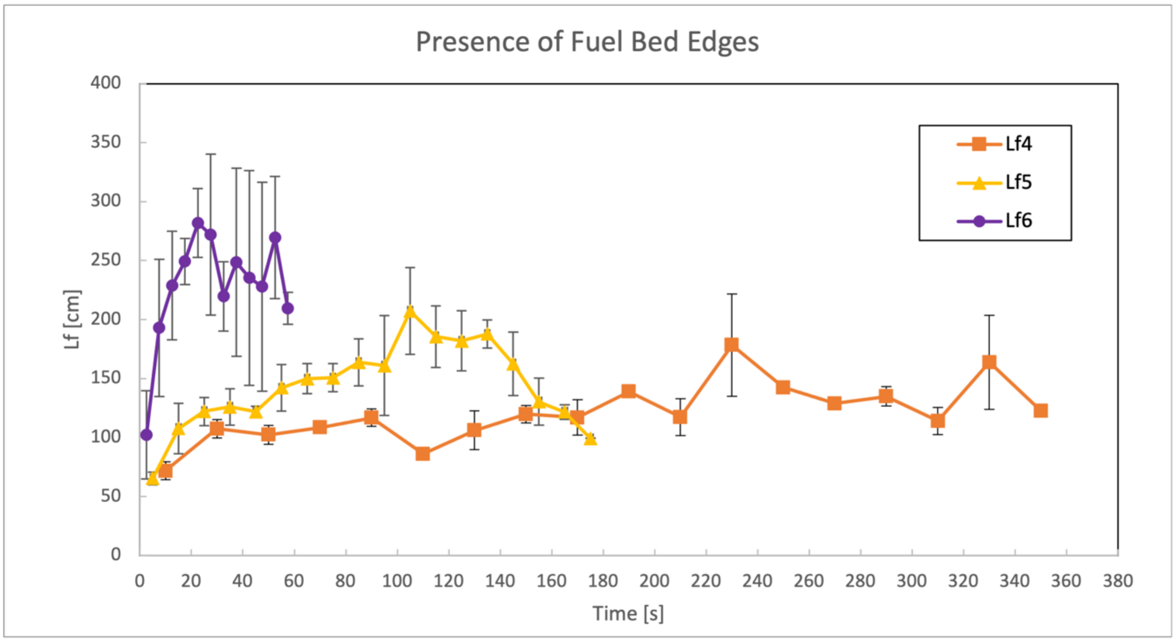


Figure 4.13. Representation of the Different Lengths of Flame with Fuel Bed Edges

The graphic shows that faster flow velocities generate greater flame length values. This, as in the section 4.1 where the experimental tests were performed without fuel bed edges, matches the rate of spread and fire intensity analyses, and leads us to the conclusion that faster wind speeds generate higher values of rate of spread and flame length, and, consequently, higher values of fireline and fire intensity.

4.2.6. Analysis of Fire Intensity for Different Flow Velocities

For this section, the fire intensity values can be observed as they were determined after having the flame length values. The fire intensity was determined with resort to the equation (2.4).

The determined fire intensity can be analyzed using the Figure 4.14.

For this analysis, the fire intensity values of all experimental tests were compilated and divided by the different flow velocities they were performed for (0,1 and 3m/s). The graphic series, I_{b4}, I_{b5} and I_{b6}, correspond to the average values of fire intensity of each experiment, respectively.

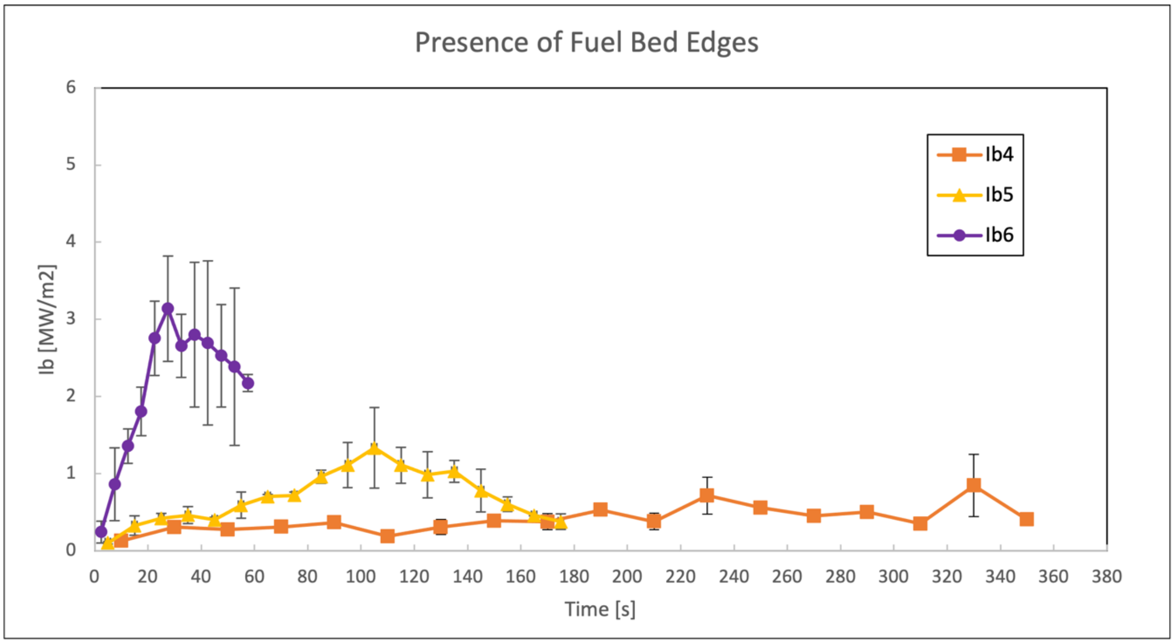


Figure 4.14. Representation of the Different Fire Intensities with Fuel Bed Edges

Contrarily of what was observed for the experimental tests performed without fuel bed edges, for the tests performed with fuel bed edges the maximum value of fire intensity is greater than the maximum value of fireline intensity except for a flow velocity of 3 m/s. In this case, we can also notice that the sum of the fire intensity values is always greater than the sum of the fireline intensity values.

To have an easier observation of these affirmations, the maximum values, and the sum of the values for fireline and fire intensity can be observed in the Table 4.2.

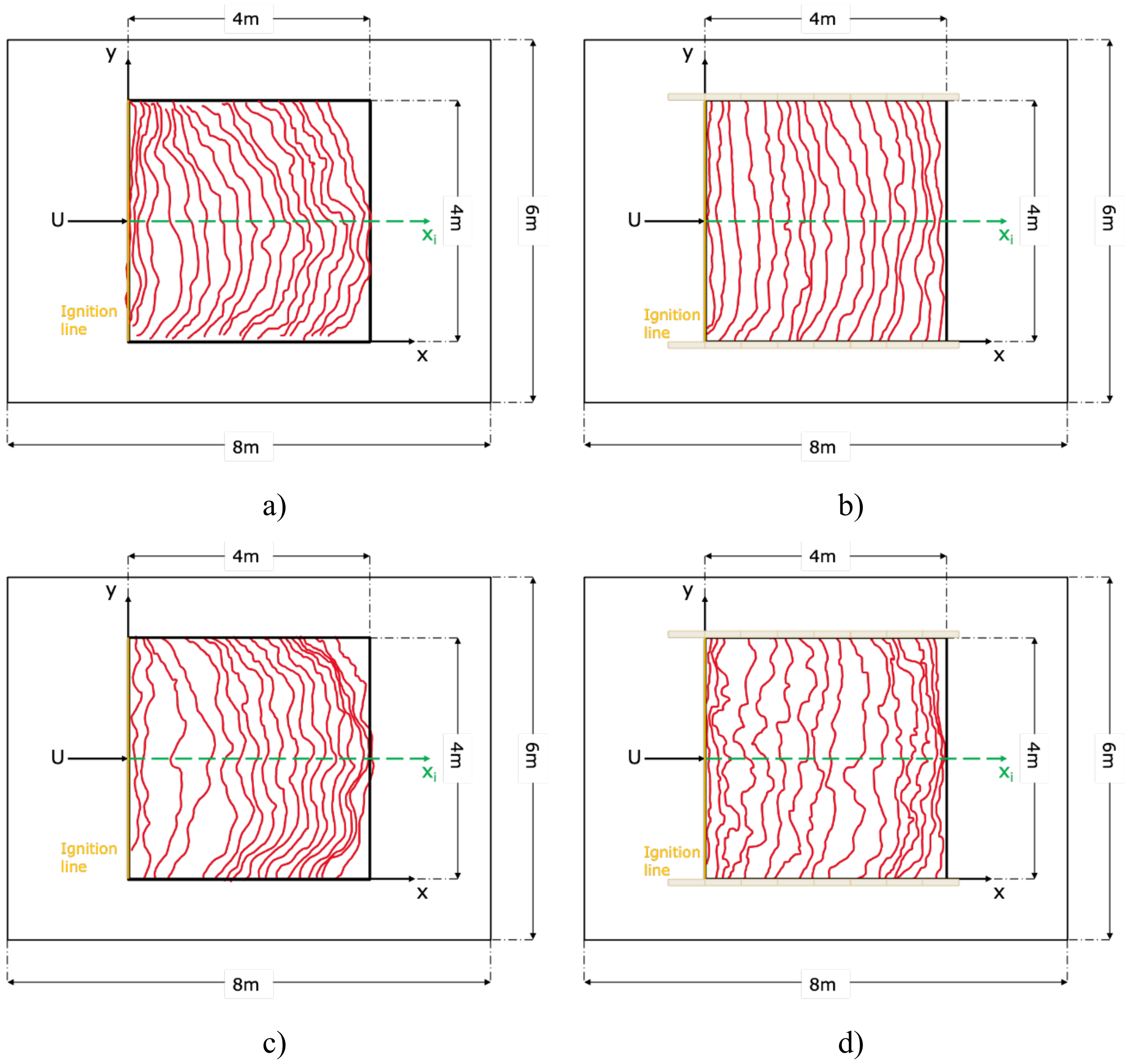
Table 4.2. Comparation Between Fireline and Fire Intensity with Fuel Bed Edges

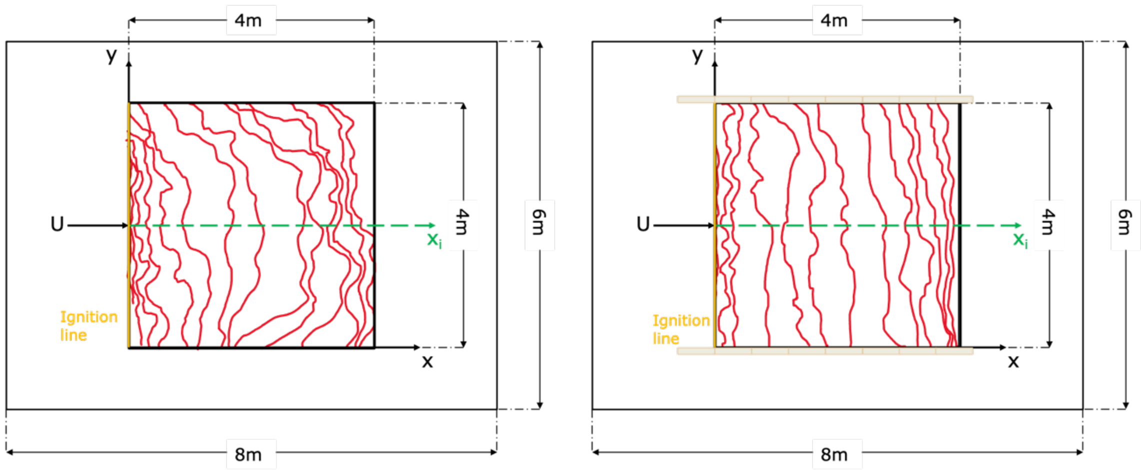
Experiment	Fireline Intensity [MW/m]		Fire Intensity [MW/m^2]	
	Maximum Value	Sum	Maximum Value	Sum
4	0.49	6.06	0.85	7.40
5	1.20	12.09	1.33	12.49
6	4.16	23.70	3.14	25.42

4.3. Results Comparison

In this section, the comparison between the different configurations for the same flow velocities is going to be made. After comparing the tests with same flow velocities with each other, the fireline and fire intensity values are going to be compilated in a table to better analyze the difference that adding fuel bed edges makes.

Before proceeding to the comparison of values, it is already possible to analyze the fire spread profile, observing the Figure 4.15.





e) f)

Figure 4.15. Representation of the Fire Spread with and without Fuel Bed Edges for Different Flow Velocities

Table 4.3. Label of Each Picture of the Figure 4.15

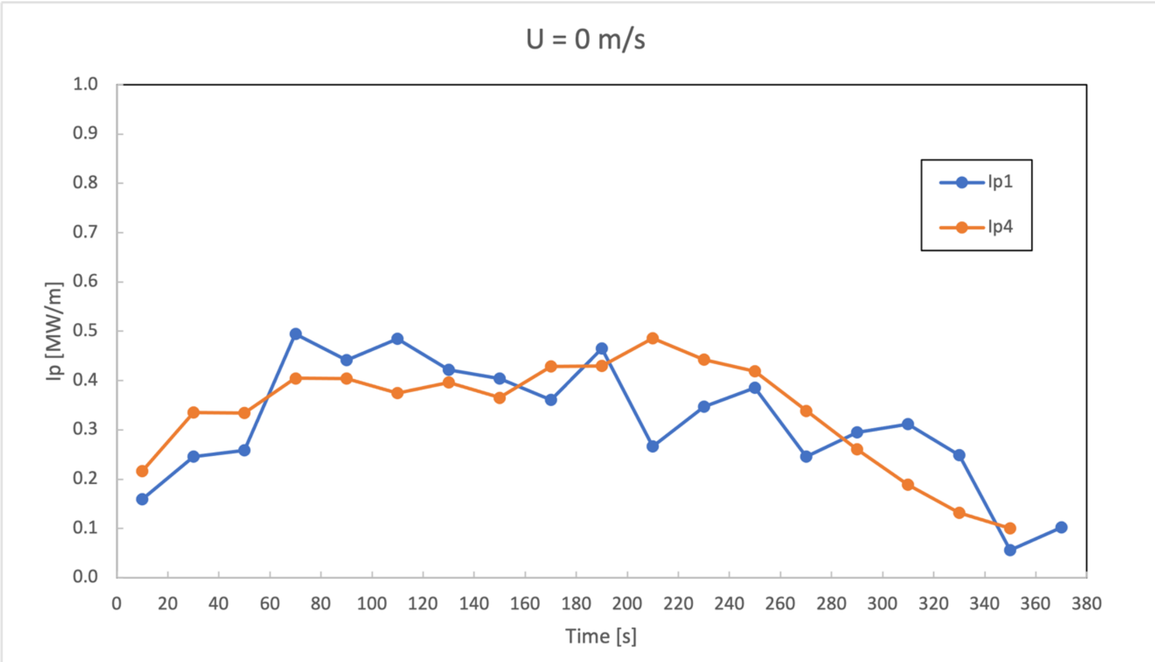
	Reference	**Fuel Bed Edges [YES/NO]**	**Flow Velocity [m/s]**
a)	Experiment 1	No	0
b)	Experiment 4	Yes	0
c)	Experiment 2	No	1
d)	Experiment 5	Yes	1
e)	Experiment 3	No	3
f)	Experiment 6	Yes	3

Analyzing the pictures of the Figure 4.15 it is possible to notice that the spread of the fire has a more linear front when the fuel bed edges are present, showing that these fuel bed edges really offer a path for the fire to follow, burning the whole fuel bed more efficiently. So, it is expected to have greater fireline and fire intensities when the fuel bed edges are present on the tests.

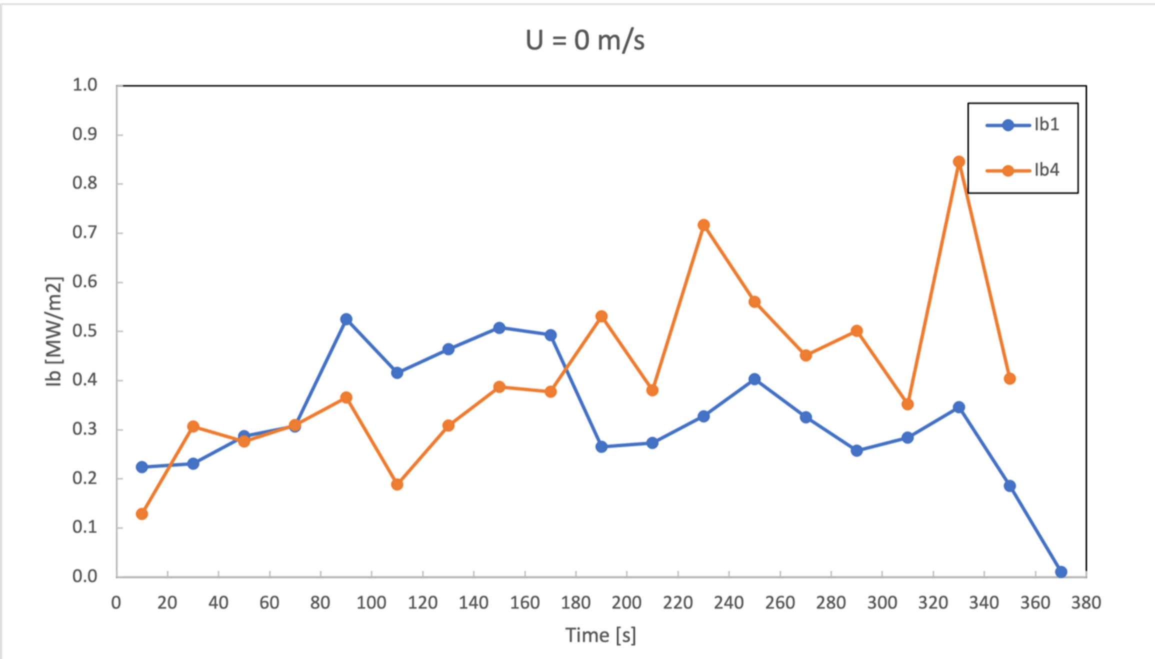
4.3.1. Results Comparison for Flow Velocity of 0 m/s

For this section, we are going to compare the fireline and fire intensities once these two aspects depend on the others and are the main results of the experiments.

The results are illustrated in the Figure 4.16.



a)



b)

Figure 4.16. Representation of a) Fireline Intensity and b) Fire Intensity for a Flow Velocity of 0 m/s

Observing the results in the figure, for a flow velocity of 0 m/s, the maximum fireline intensity value is the same for both configurations (0.49 MW/m), while the maximum fire intensity value is higher when the fuel bed edges are present. Another aspect observed is that the sum of fireline and fire intensities is higher when we use fuel bed edges.

This analysis can be observed at the Table 4.4.

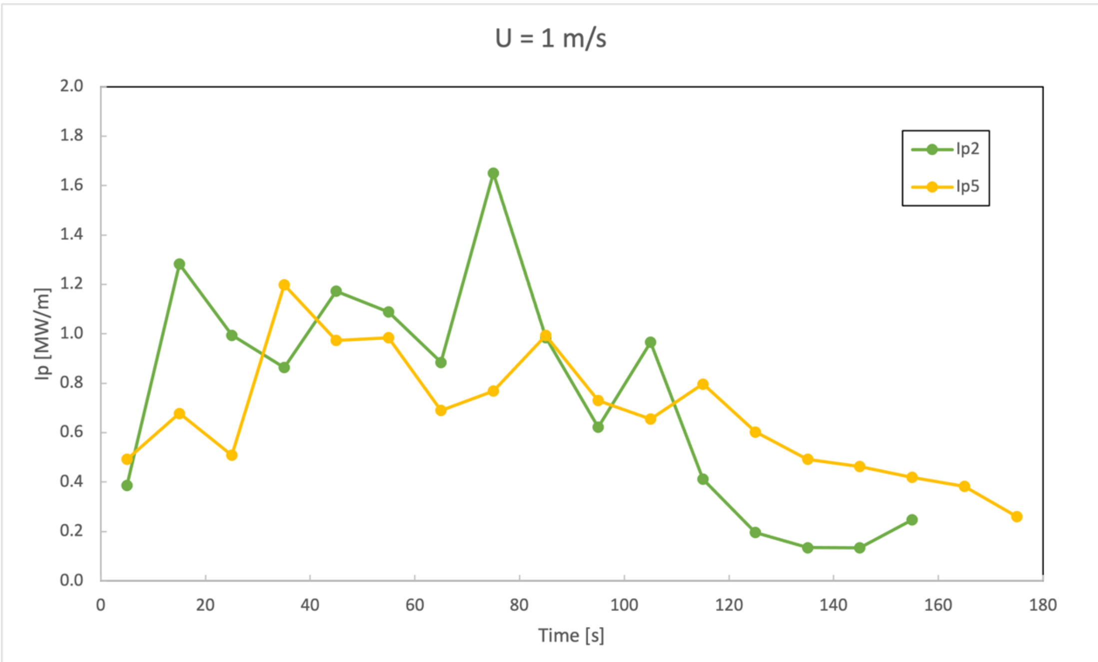
Table 4.4. Comparation of Fireline and Fire Intensity for Different Configurations and 0 m/s Flow Velocity

Experiment	Fireline Intensity [MW/m]		Fire Intensity [MW/m^2]	
	Maximum Value	Sum	Maximum Value	Sum
1	0.49	6.00	0.53	6.14
4	0.49	6.06	0.85	7.40

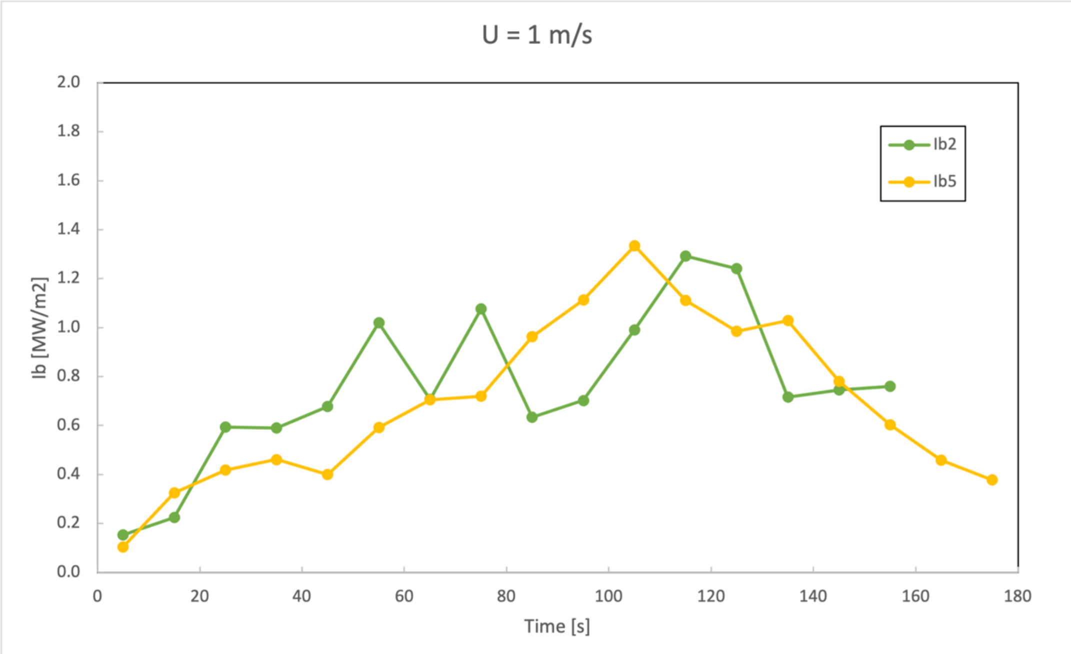
4.3.2. Results Comparison for Flow Velocity of 1 m/s

In this section, the comparation between the fireline and fire intensities continues to be made for the same reason as it was explained in the previous section.

The Figure 4.17 illustrates the fireline intensity and also the fire intensity.



a)



b)

Figure 4.17. Representation of a) Fireline Intensity and b) Fire Intensity for a Flow Velocity of 1 m/s

Contrary to what was observed in the previous section about the maximum value of the fireline intensity, for a flow velocity of 1 m/s, is higher when there are no fuel bed edges, while the maximum value of fire intensity continues to be higher when in the presence of fuel bed edges.

What continues to be observed is that the sum both of the fireline and fire intensity continues to be higher when the fuel bed edges are used.

The results are presented in Table 4.5.

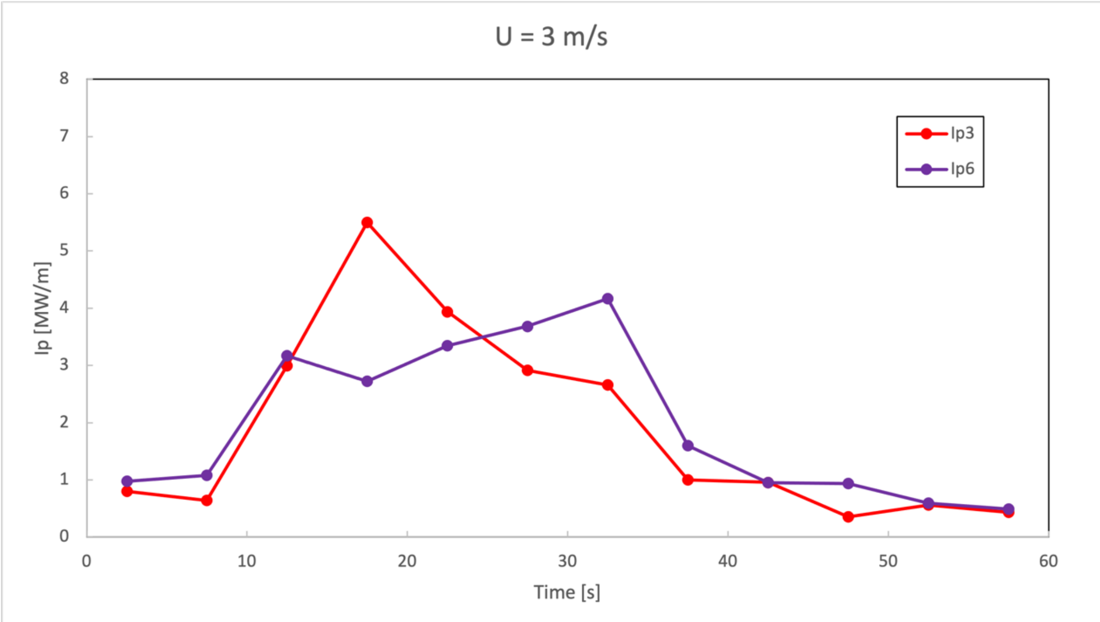
Table 4.5. Comparation of Fireline and Fire Intensity for Different Configurations and 1 m/s Flow Velocity

Experiment	Fireline Intensity [MW/m]		Fire Intensity [MW/m^2]	
	Maximum Value	Sum	Maximum Value	Sum
2	1.65	12.02	1.29	12.13
5	1.20	12.09	1.33	12.49

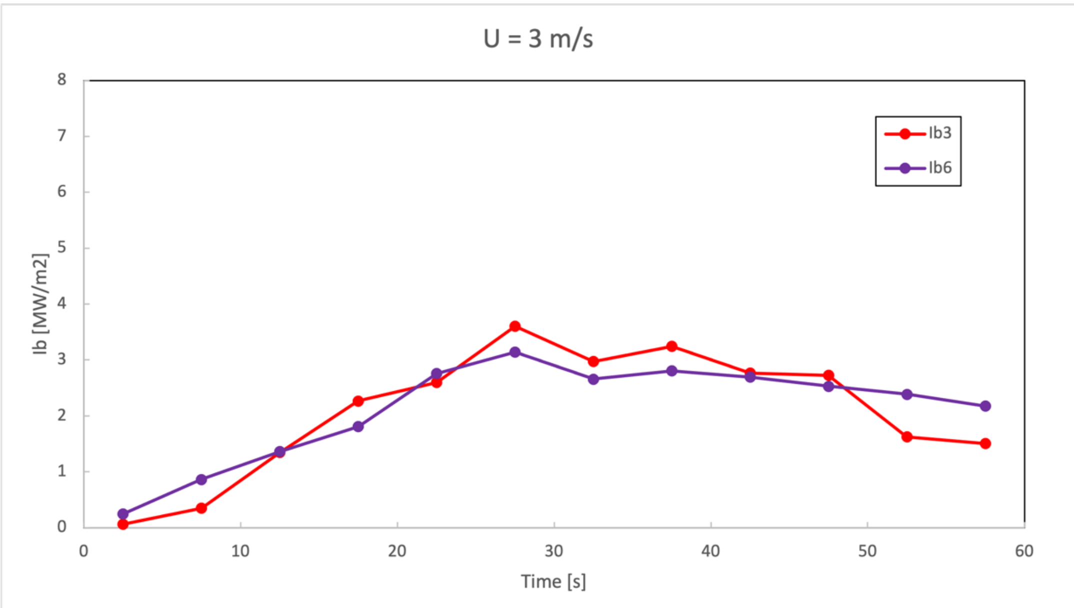
4.3.3. Results Comparison for Flow Velocity of 3 m/s

In this section, we continue to compare the fireline and fire intensities, now for a flow velocity of 3 m/s.

The results can be observed in Figure 4.18.



a)



b)

Figure 4.18. Representation of a) Fireline Intensity and b) Fire Intensity for a Flow Velocity of 3 m/s

For a flow velocity of 3 m/s we can observe that the maximum value either for fireline intensity or for fire intensity is reached when there is no presence of fuel bed edges, while the sum of both intensities continues to be higher when we use fuel bed edges.

The results are compiled in Table 4.6 for a better understanding.

Table 4.6. Comparation of Fireline and Fire Intensity for Different Configurations and 3 m/s Flow Velocity

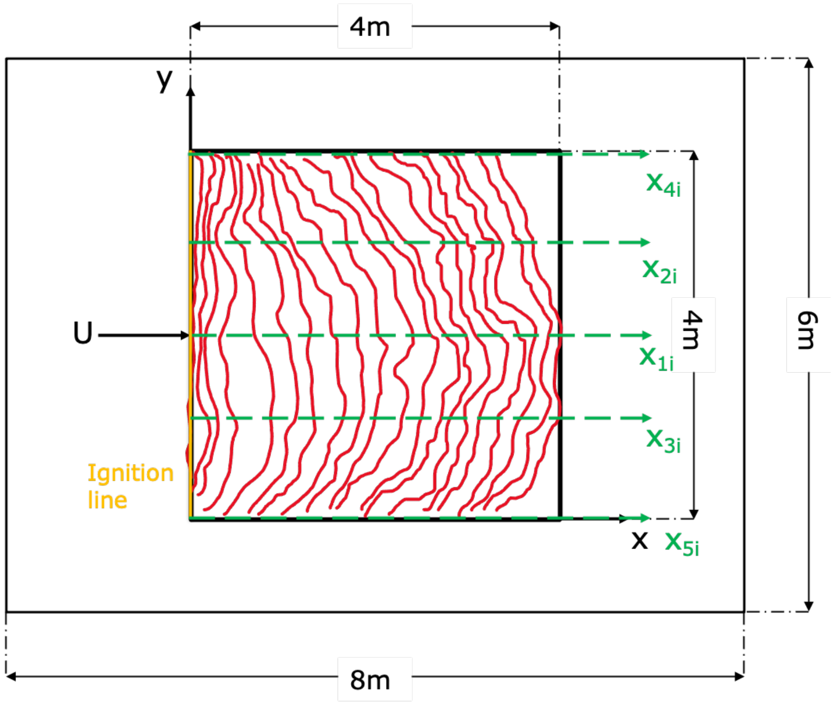
Experiment	Fireline Intensity [MW/m]		Fire Intensity [MW/m^2]	
	Maximum Value	Sum	Maximum Value	Sum
3	5.50	22.74	3.60	25.04
6	4.16	23.70	3.14	25.42

4.3.4. Compilation of All Experimental Tests

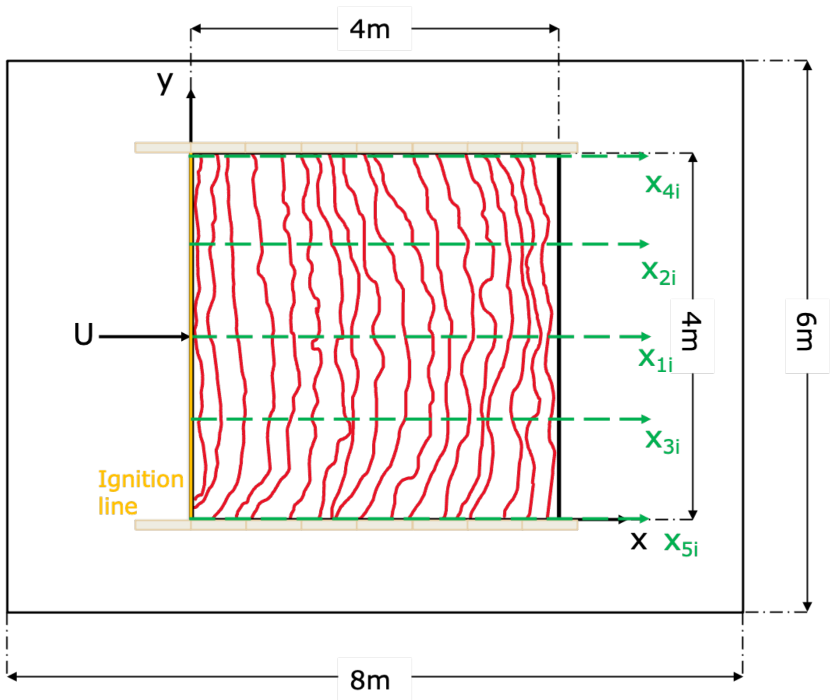
The results of the six experiments are compiled in the

Experiment	Fireline Intensity [MW/m]		Fire Intensity [MW/m^2]		Fuel Bed Edges [Yes/No]	Flow Velocity [m/s]
	Maximum Value	Sum	Maximum Value	Sum		
1	0.49	6.00	0.53	6.14	No	0
2	1.65	12.02	1.29	12.13	No	1
3	5.50	22.74	3.60	25.04	No	3
4	0.49	6.06	0.85	7.40	Yes	0
5	1.20	12.09	1.33	12.49	Yes	1
6	4.16	23.70	3.14	25.42	Yes	3

After analyzing the fireline and fire intensities we observe that, besides the sums of values are higher when the fuel bed edges are used, the maximum values present some inconsistency. This is due to the ROS has been measured only for the central axis of the fuel bed. To have more reliable results we proceed to a measurement using five axis (one in the center of the fuel bed, two distanced from this one 1 m for each side, and one for each extremity of the fuel bed) and use the average values of the ROS for each experiment. This will help us observe if the general ROS values are higher when there are fuel bed edges present, as expected. The optimized representation can be observed in Figure 4.19.



a)



b)

Figure 4.19. Optimized Representation of the Measurements Made to Determine the ROS a) without Fuel Bed Edges and b) with Fuel Bed Edges

4.3.5. Comparation of Optimized Measures for Flow Velocities of 3 m/s

In this section, we are now going to compare the values of the ROS and the fireline intensities using optimized measurements. Once the values of fire intensity showed a more accentuated difference between configurations, we concluded that there was a necessity of additional measurements in order to have more reliable values of the ROS and, consequently, the fireline intensity.

So, the optimized values of the ROS and fireline intensity can be observed in Figure 4.20 and Figure 4.21, respectively.

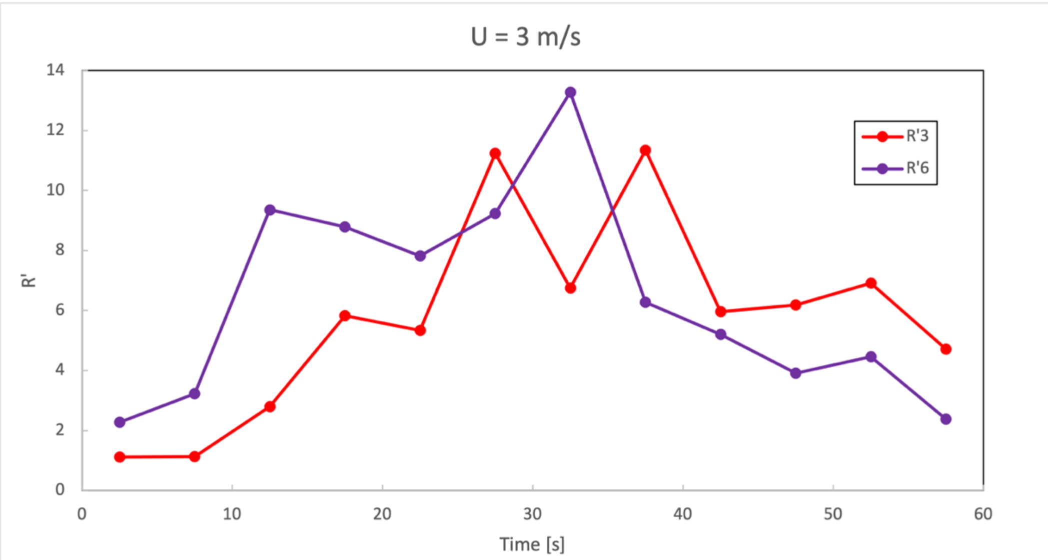


Figure 4.20. Comparation of the Optimized ROS Values for Flow Velocity of 3 m/s

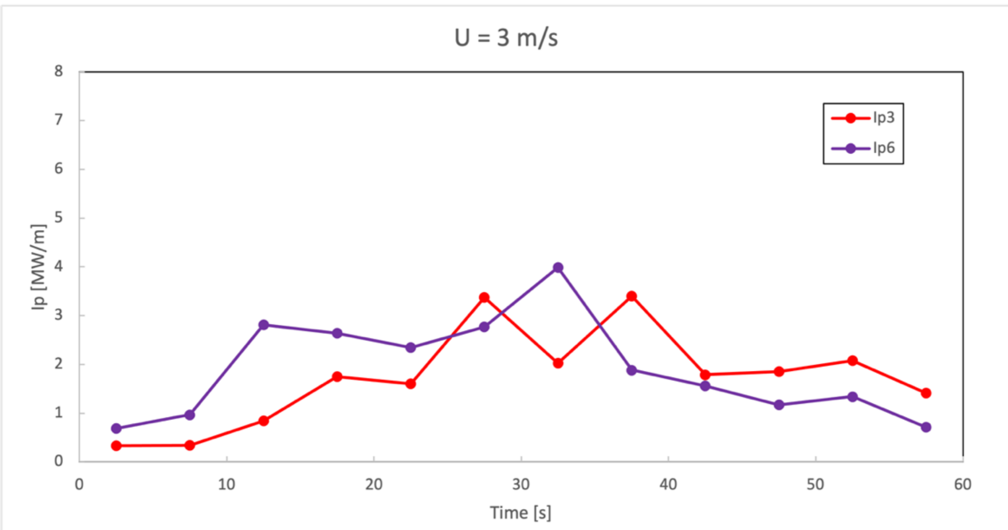


Figure 4.21. Comparation of the Optimized Fireline Intensity Values for Flow Velocity of 3 m/s

As expected, the maximum values of the ROS and fireline intensity are now higher when the fuel bed edges are present, once for this configuration the fire has a more linear way to spread, and this difference can be really noted on the extremities of the fuel bed.

The sum of the values remains higher for the configuration with fuel bed edges.

4.3.6. Comparation of Optimized Measures for All Flow Velocities

In this section, the maximum values of the rate of spread and fireline intensity are going to be analyzed as well as the sum values for each experiment. This way it is possible to conclude if the ROS and the fireline intensity are really higher when the fuel bed edges are present. The graphics for flow velocities of 0 m/s and 1 m/s can be observed at the ANNEX B.

The maximum values as well as the sum of the values of the ROS and fireline intensity are presented in Table 4.7.

Table 4.7. Comparation of Maximum and Sum Values of the ROS and Fireline Intensity for Optimized Measurements

Experiment	Fireline Intensity [MW/m]		Rate of Spread		Fuel Bed Edges [Yes/No]	Flow Velocity [m/s]
	Maximum Value	Sum	Maximum Value	Sum		
1	0.42	5.25	1.39	17.51	No	0
2	1.15	10.52	3.82	35.08	No	1
3	3.40	20.80	11.34	69.32	No	3
4	0.47	5.83	1.56	19.43	Yes	0
5	1.17	11.62	3.88	38.73	Yes	1
6	3.98	22.86	13.28	76.21	Yes	3

Analyzing the data on the table it is possible to confirm that the rate of spread has higher values when the fuel bed edges are present. This was possible to observe after first analyze the fire intensity values, as these showed that the intensity is higher with the presence of fuel bed edges and according to Byram (1959) to generate more intensity, the Rate of Spread must have higher values.

This helps us conclude that fuel bed edges really give a path for the fire to follow and, consequently, spreads faster because of the linear profile of the fire front.

5. CONCLUSIONS

The objective of this dissertation was the study of the effect of fuel bed edges on fire dynamics in wind tunnel with the main goal of understand how much of a difference does the fuel bed edges make to the fire so this one has a behavior closer to the reality.

For this study two different factors that influence the fire behavior were analyzed. These were, as already mentioned, the flow velocity and the presence of fuel bed edges.

What we first notice was that, with fuel bed edges, the fire propagation is linear and has a homogenic fire front extension looking like a portion of a great forest fire. This was not verified without fuel bed edges, leading us to conclude that fuel bed edges really help to reproduce a better representation of a forest fire. This had to, posteriorly, be proven with resort to the values of rate of spread, fireline intensity, flame length and fire intensity.

As to the flow velocity, as expected, when it increased all the analyzed parameters of the fire, such as rate of fire, fireline intensity, height, tilt and length of the flames, and fire intensity, also increased once the flow direction was the same of the propagation direction.

As to the presence of fuel bed it was expected that all the parameters also increased once the fuel bed edges give a path for the fire to follow, but in an earlier analysis this didn't verify. And it was thanks to the analysis of the fire intensity that we concluded that another measures should be made in order to confirm the theory that the fire behavior is closer to the reality when we use fuel bed edges.

After proceeding to the optimized measurements, as mentioned in section 4.3.4, it was possible to conclude that when the fuel bed edges are added all the parameters increased, when compared to the tests without fuel bed edges.

Comparing all the analyzed data it is possible to conclude that, in fact, when we use fuel bed edges the fire presents an extreme behavior, presenting higher values of ROS and higher intensities either for fire or fireline.

This leads us to conclude that the presence of fuel bed edges produces a fire behavior closer to a forest fire.

This thesis can be used as a source for future modeling works as well as an important data base about fire behavior.

For further studies, it would be interesting to introduce another factors, such as terrain slope or more than one fire front, to verify if the fuel bed edges help to produce a behavior closer to a real one or if it was just for this particular study.

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ANNEX A

In the annex there are the graphics of each flow velocity that were used to analyze the different aspects of the fire behavior.

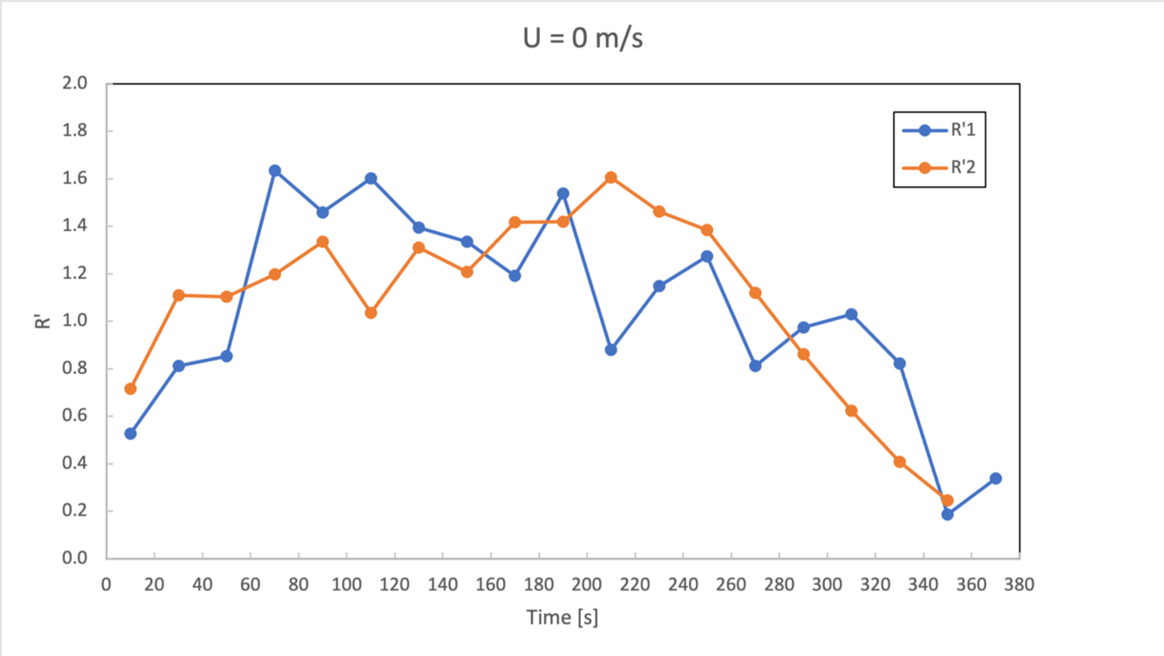

Figure 0.1. Representation of ROS for a Flow Velocity of 0 m/s

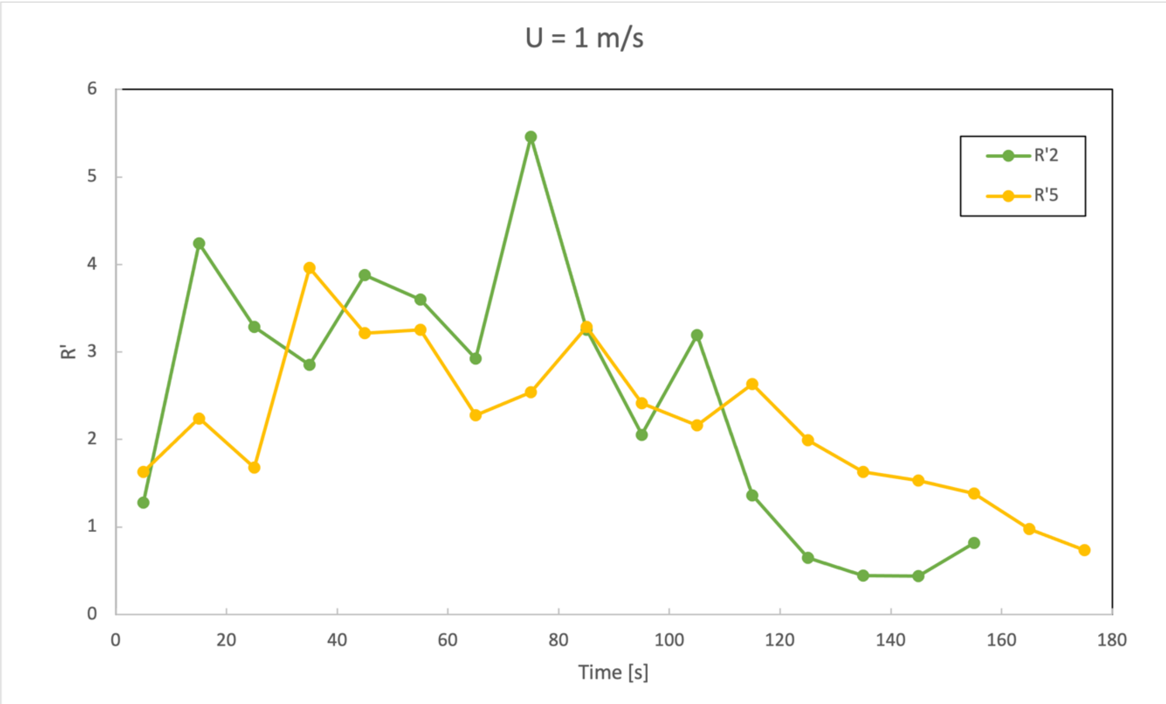

Figure 0.2. Representation of ROS for a Flow Velocity of 1 m/s

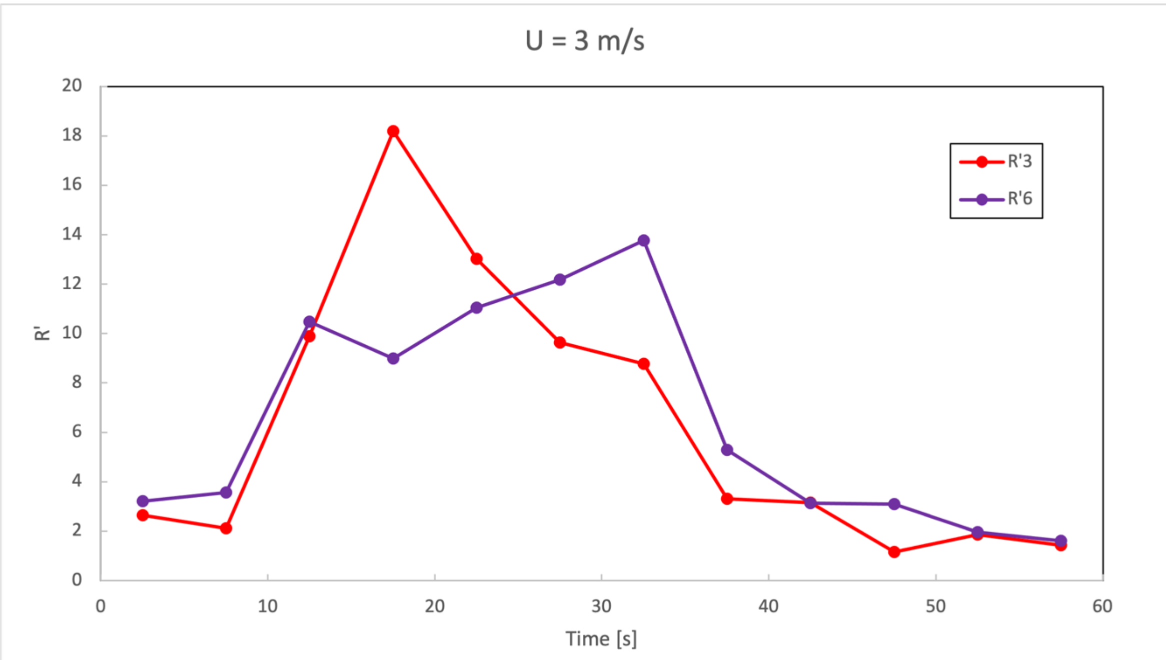

Figure 0.3. Representation of ROS for a Flow Velocity of 3 m/s

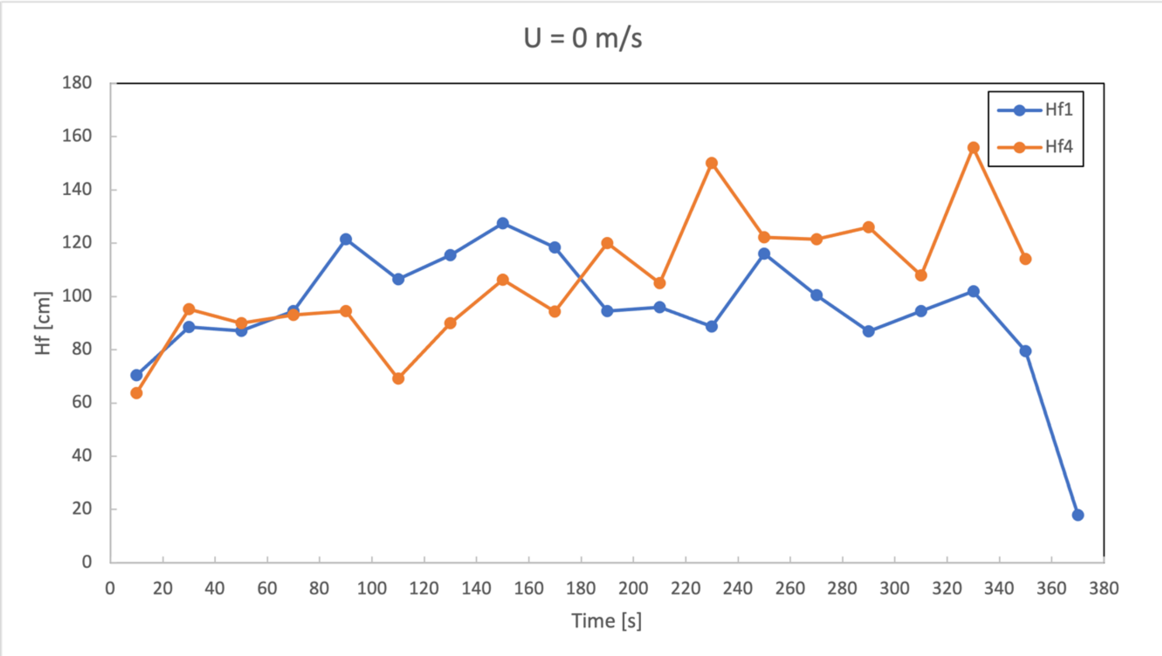

Figure 0.4. Representation of Flame Height for a Flow Velocity of 0 m/s

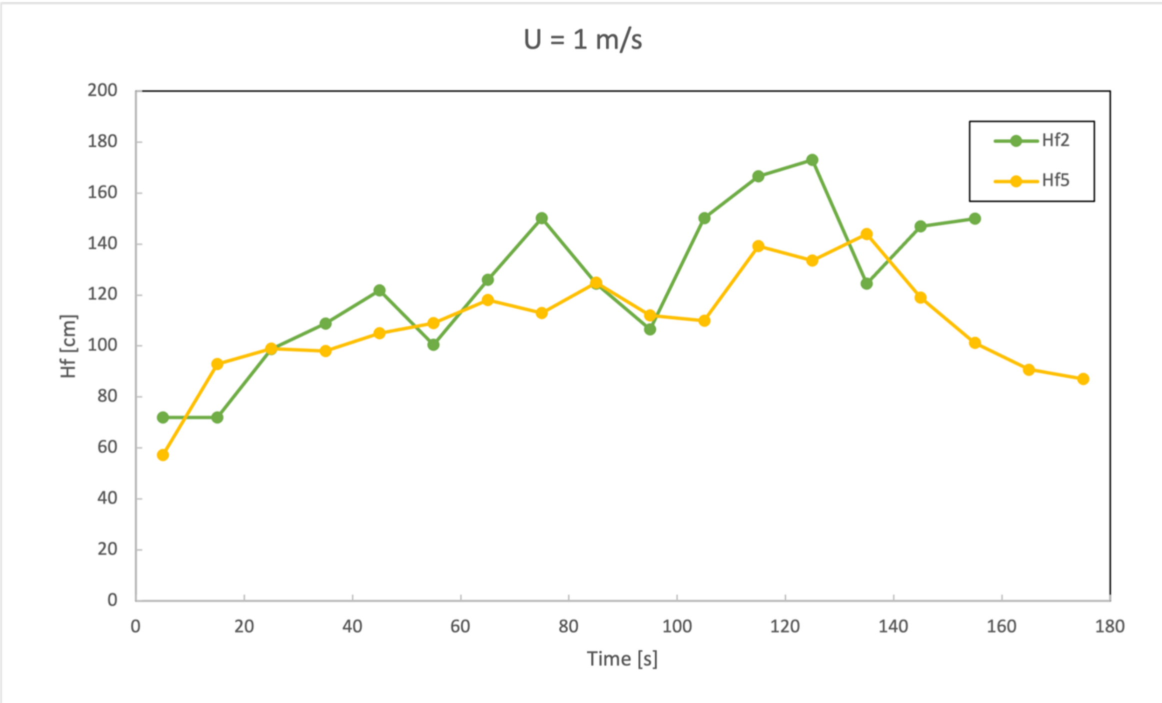

Figure 0.5. Representation of Flame Height for a Flow Velocity of 1 m/s

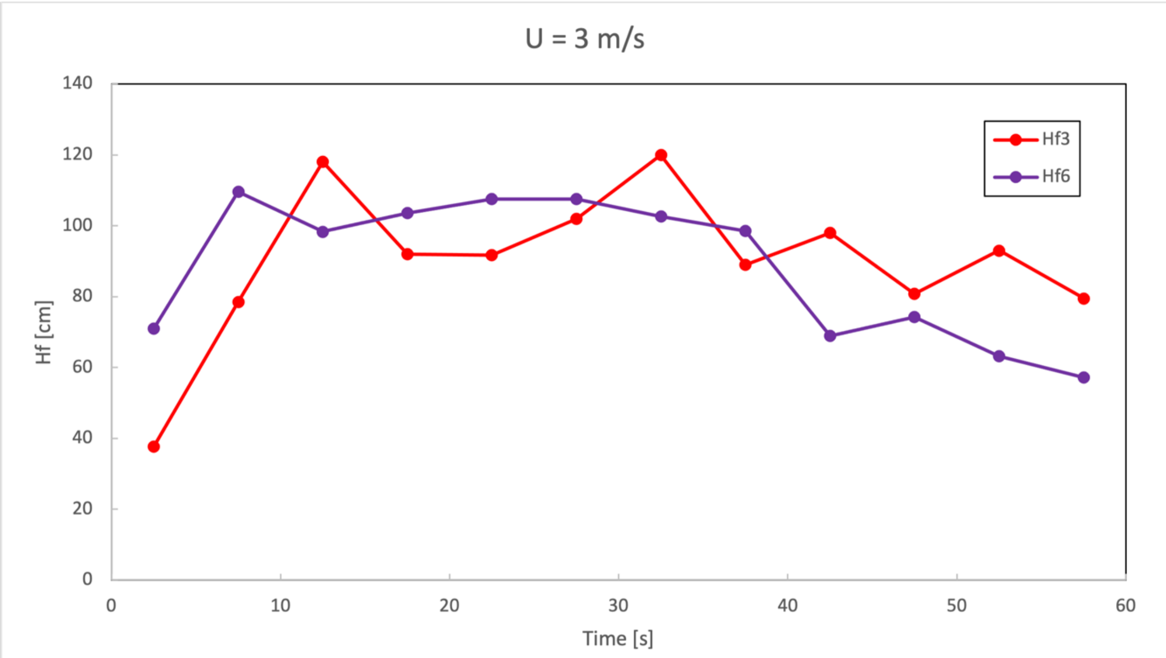

Figure 0.6. Representation of Flame Height for a Flow Velocity of 3 m/s

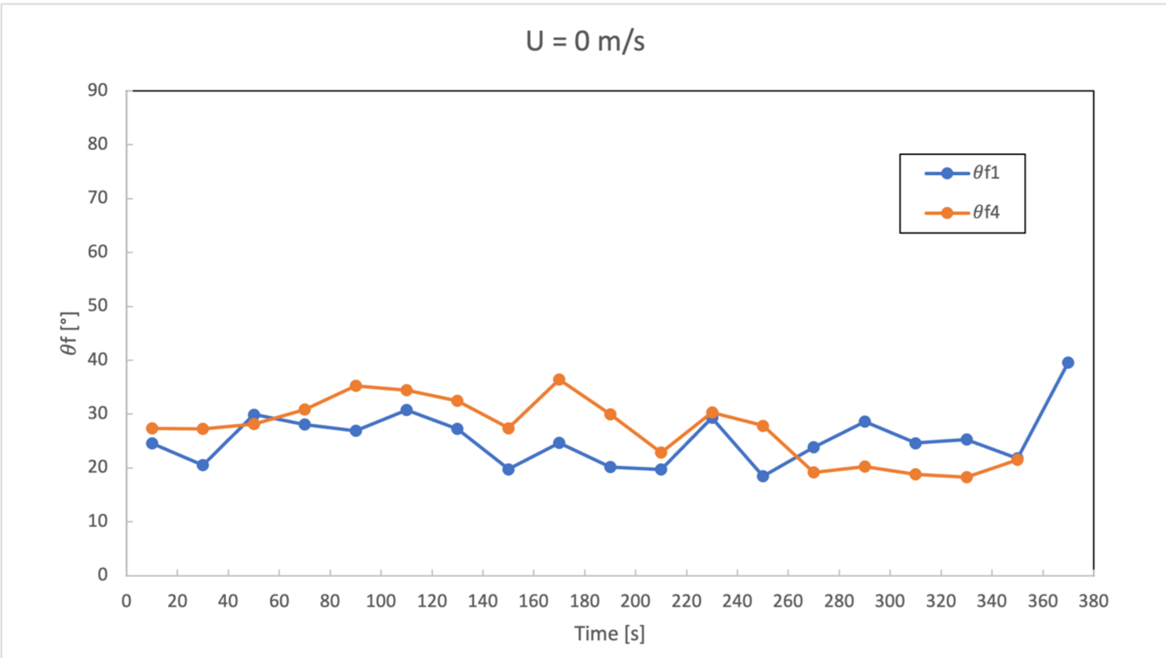

Figure 0.7. Representation of Flame Tilt for a Flow Velocity of 0 m/s

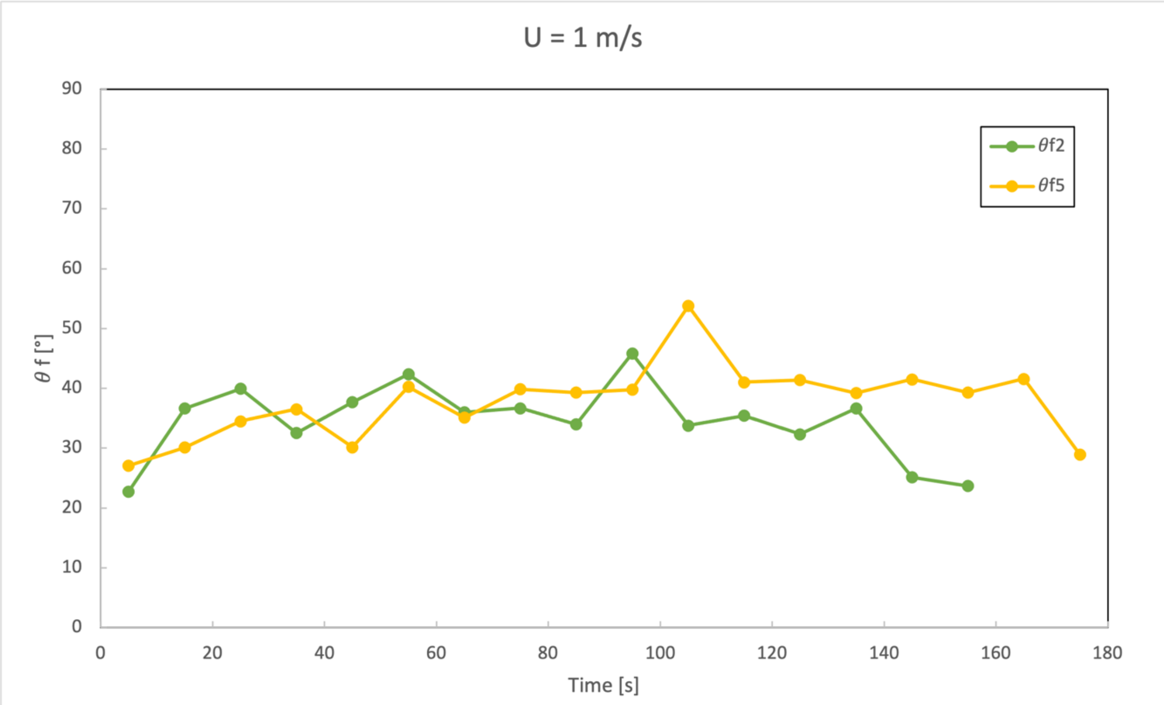

Figure 0.8. Representation of Flame Tilt for a Flow Velocity of 1 m/s

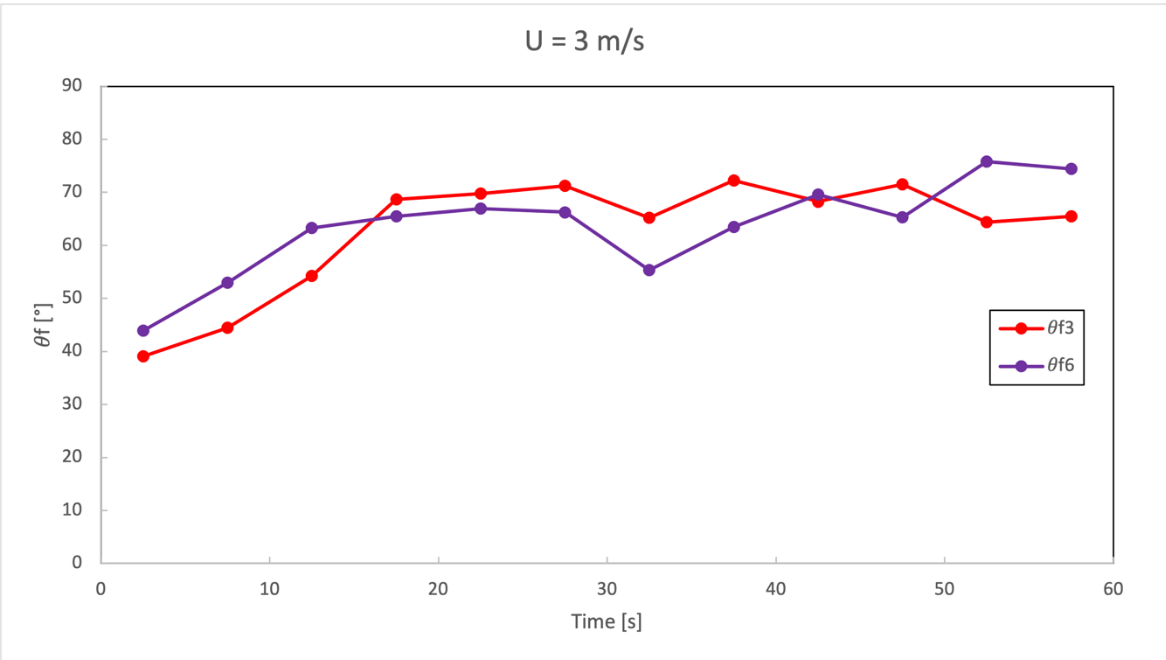

Figure 0.9. Representation of Flame Tilt for a Flow Velocity of 3 m/s

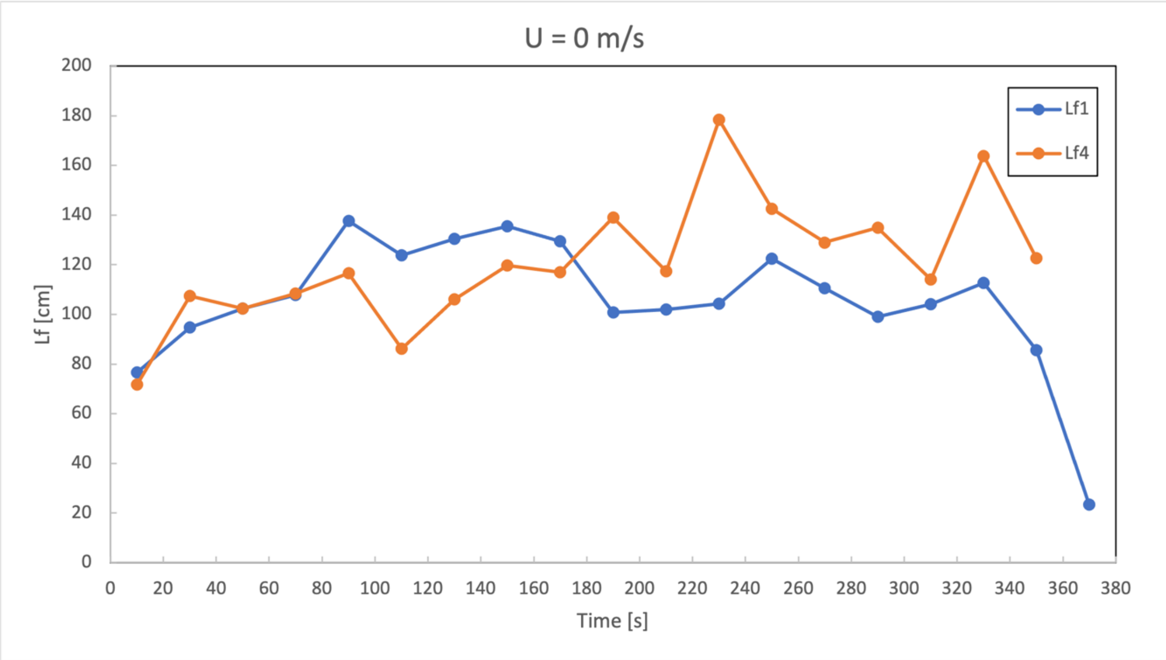

Figure 0.10. Representation of Flame Length for a Flow Velocity of 0 m/s

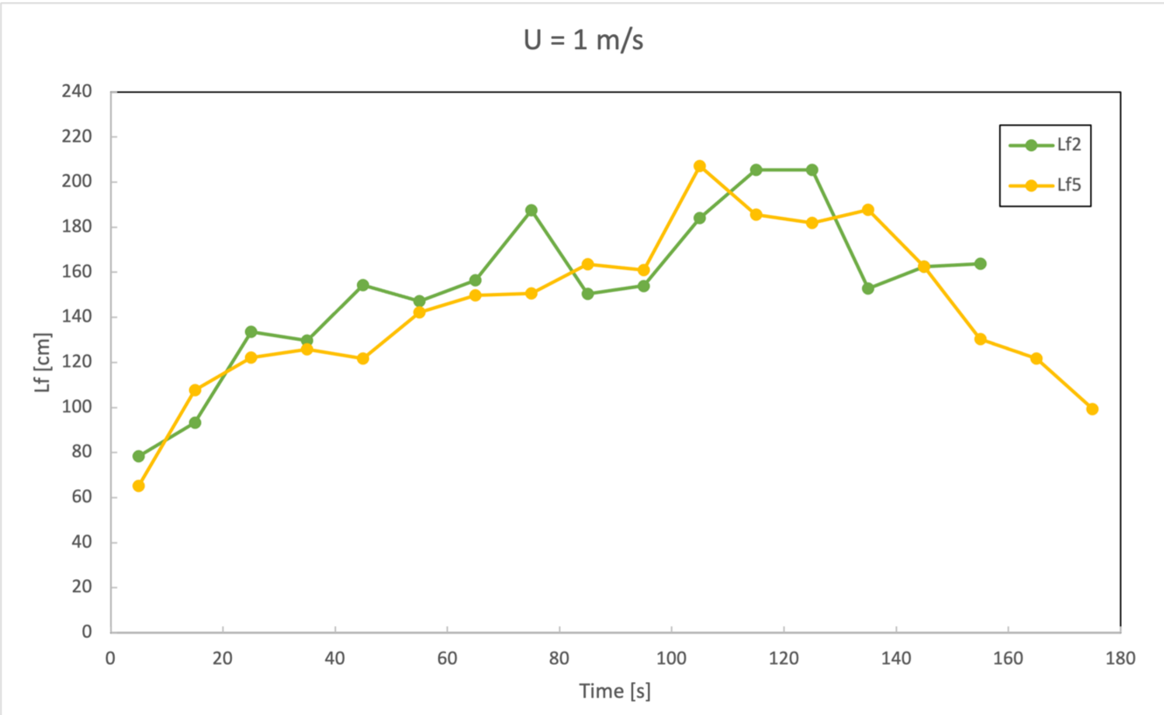

Figure 0.11. Representation of Flame Length for a Flow Velocity of 1 m/s

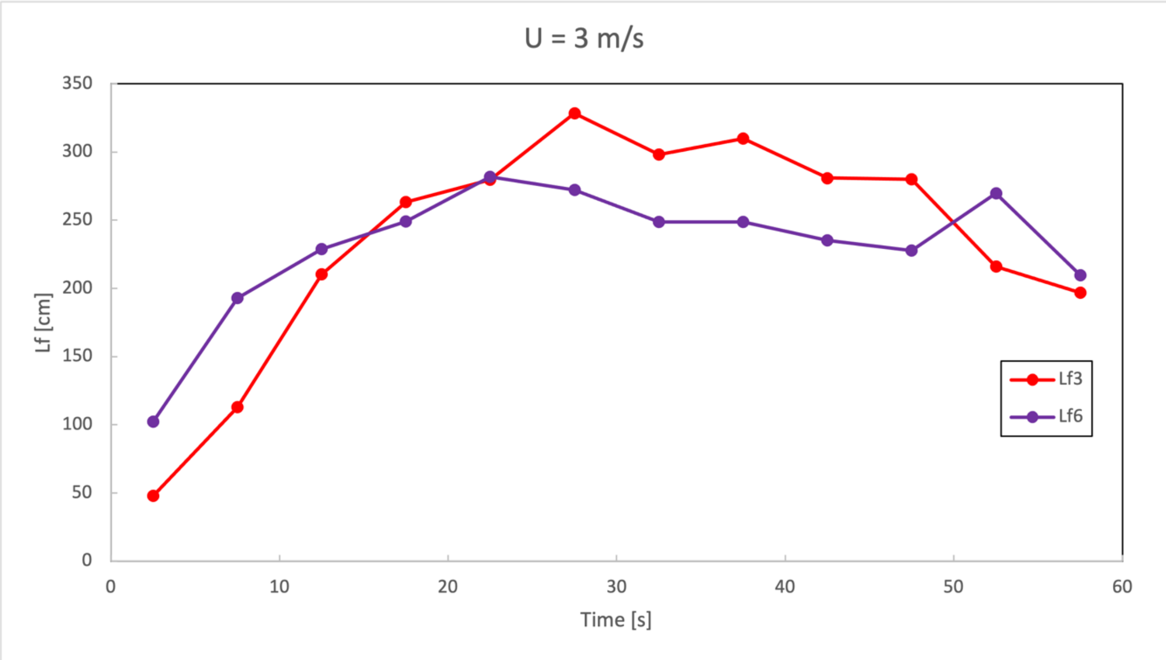

Figure 0.12. Representation of Flame Length for a Flow Velocity of 3 m/s

ANNEX B

In this annex are the graphics of the comparation of optimized ROS and Fireline Intensity values for flow velocities of 0 m/s and 1 m/s.

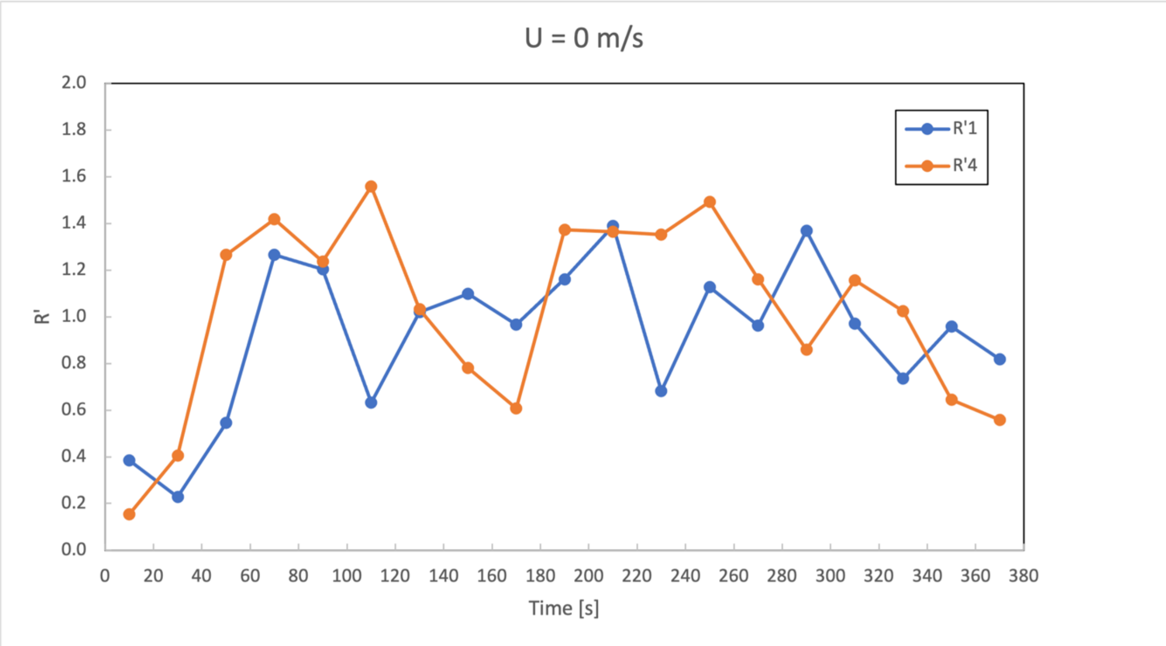

Figure 0.1. Comparation of the Optimized ROS Values for Flow Velocity of 0 m/s

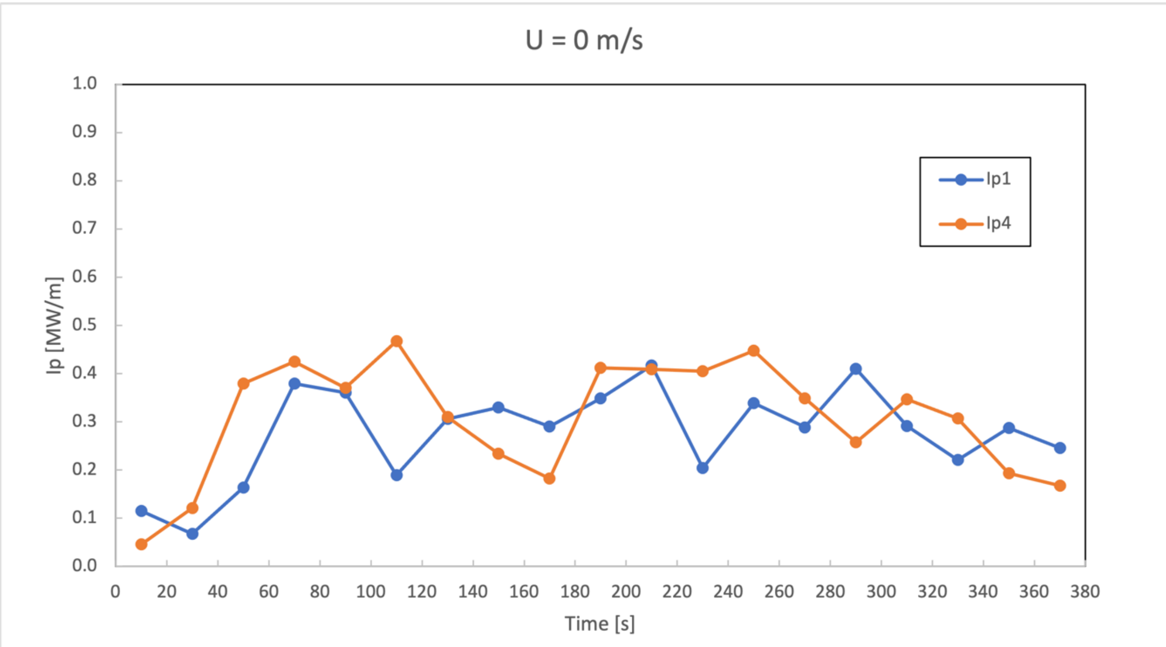

Figure 0.2. Comparation of the Optimized Fireline Intensity Values for Flow Velocity of 0 m/s

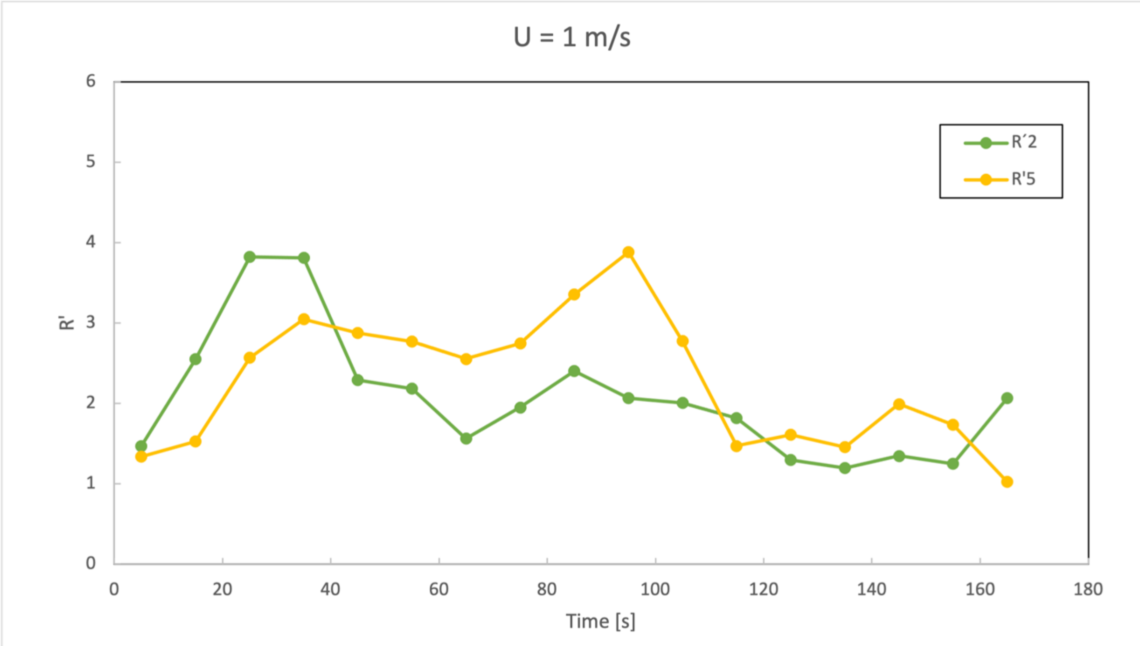

Figure 0.3. Comparation of the Optimized ROS Values for Flow Velocity of 1 m/s

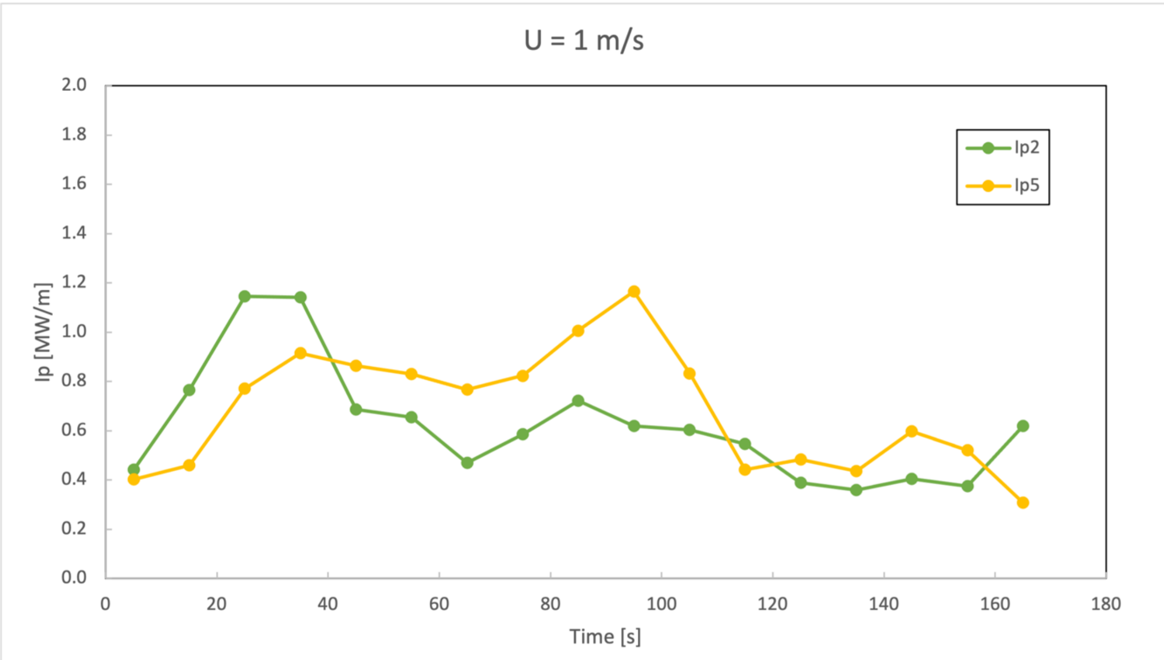

Figure 0.4. Comparation of the Optimized Fireline Intensity Values for Flow Velocity of 1 m/s