



Modelling the probability of smouldering ignition of vegetation from hot metal particles ejected by power lines

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ABSTRACT

Power line failures can cause wildfires, particularly in regions like California, Australia, and Portugal, where high-wind conditions have led to the clash of power line conductors, ejecting metal particles that can ignite nearby vegetation. While ignition by particles has been the focus of experiments before, its modelling remains understudied. This paper presents a computational model to predict ignition by particles, focusing on smouldering as the critical stage before flaming. Particle trajectory and cooling in flight are simulated stochastically using equations of motion and heat transfer, while ignition of vegetation is modelled through a pseudo-one-dimensional thermochemical medium with Gpyro. Using weather and fuel data from California as a case study, results show that for wind speeds up to 20 m/s, aluminium particles with a diameter of at least 6.5 mm, ejected from a 20 m high power line, land at temperatures above 740 °C and can ignite grass and shrub fuel beds, creating an at-risk zone of 274 m² around the conductor clash point, extending up to 52 m from the power line. Fuel moisture is the primary factor influencing ignition, followed by particle size. This modelling study contributes to close the gap in modelling ignition by particles and offers insights for mitigating wildfire hazards from power lines.

1. Introduction

Wildfires are natural hazards that occur worldwide, often leaving a trail of devastation that impacts human lives, infrastructures, and ecosystems, and climate change has contributed significantly to its increasing occurrence and severity [1]. An alarming number of wildfires caused by power line failure have been observed in various regions of the world, including California, Chile, Spain, China, Australia, and Portugal [2–4]. These regions experience prolonged droughts, dry vegetation, intense heat waves, and strong winds, creating ideal conditions for severe wildfires. Although power lines are not the leading cause of wildfires, the fires they ignite tend to be highly destructive: in California, power lines are estimated to cause only 1% of wildfires but are responsible for over 10% of the total area burned [3]. Notably, the infamous 2018 Camp Fire, the deadliest and most destructive wildfire in California, was initiated by a faulty power line.

Power lines can initiate wildfires through various mechanisms, such as conductor clashing or contact with vegetation and animals. These events often produce hot particles, either metallic fragments or firebrands, which can travel through the air and ignite vegetation upon landing. This ignition pathway closely resembles the spot fire phenomenon observed in wildland fires, where firebrands are transported ahead of the fire front, and ignite new fires. In this study, the focus

is on hot metal particles produced during conductor clashing events. Hot metal particles are ejected during arcing, as illustrated in Fig. 1. Several studies have explored the mechanisms through which power line failure can ignite vegetation, often breaking the phenomenon down into three processes: the generation and ejection of the metal particle, its trajectory before reaching the ground, and the ignition of vegetation upon landing. While these processes have been individually investigated, the comprehensive review by Fernandez-Pello addresses their role in wildland fire ignition by hot metal particles and firebrands [5].

1.1. Particle generation

The first step consists in understanding how a metal particle can be ejected from a power line. Metal particles are generated and emitted in the case of conductor clashing or equipment failure (see Fig. 1). When power line conductors clash and then separate, the metal at the contact point reaches its melting point, forming a bridge between phases that makes electricity flow. This process then leads to the formation of an arc and the ejection of metal particles [6]. These can disperse into the surroundings and may eventually reach the ground [7–9].

The majority of the existing research on particle generation concerns aluminium and copper particles, as they are the main metals

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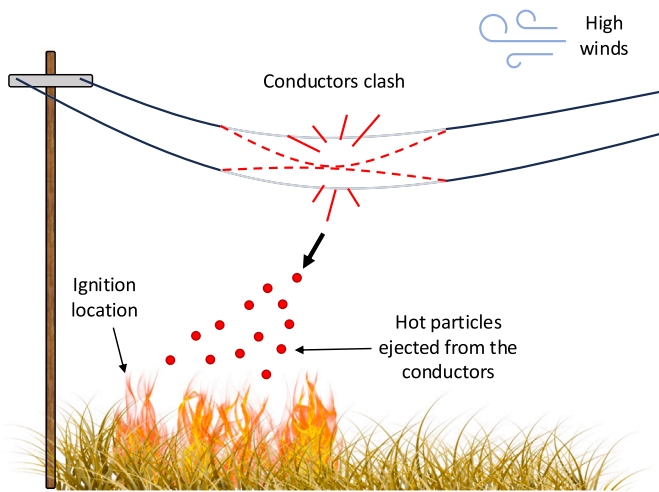


Fig. 1. Schematic of vegetation ignition by metal particles ejected after conductors clash. Hot metal particles can be generated by arcing, and can ignite vegetation upon landing.

used for conductors. Notable experiments in this area include those conducted by Blackburn [9], Ramljak et al. [8,10], Rowntree [11] and Zhu [12]. These experiments provided insights into the characteristics of ejected particles, including their size, number, and state. Particles ejected from conductors arcing typically range in size from 0.1 to 5 mm [8–11,13]. Experiments generally show that the number of particles per arcing event ranges from several dozens to over a hundred [8,9,11], with longer and more intense arcs associated with a greater number of particles emitted. Regarding particle temperature, Mills estimated the initial value to be between the melting points of aluminium and its oxide (660–2030 °C) [14], while the model of Tse and Fernandez-Pello assumed the ejected aluminium particle surface is at its boiling temperature (2480 °C) [7]. The State Electricity Commission of Victoria reported an experimentally determined initial particle temperature of 1570 °C [15]. Experiments from Rowntree [11] measured, for generated particles, higher temperatures in the range of 1700 °C to 2400 °C.

The physical state of metal particles (molten or burning) is a factor in understanding fuel ignition mechanisms. However, the literature does not agree on their state when ejected from power lines. While some models assume that aluminium particles burn in the air [7,14], others consider them to be molten [16–18]. Experimental observations, however, have identified ejected particles as molten droplets [9,11,12], though their laboratory conditions have influences the observed state. Additionally, different studies use varying assumptions about metal particle shape, with some depicting them as spherical [7,16] and others as ellipsoidal [12,17].

1.2. Particle transport

Characterising the flight path of particles identifies where they are likely to land, thereby defining *at-risk zones*, areas with a significant probability of particle deposition and potential ignition risk. The transport of metal particles shares key features with that of firebrands, which have been extensively studied in wildfire research. A pioneering contribution was made by Tarifa [19], who introduced a physics-based framework for modelling their airborne motion. In the context of metal particles, an early and noteworthy contribution is that of Mills and Hang [14], who studied the combustion rates of burning aluminium particles along with their trajectories. This was followed by the work of Tse and Fernandez-Pello, who proposed a numerical model

to characterise the flight path and combustion rates of firebrands and metal particles [7], using Newton's equations of motion.

The initial velocity of a particle is a key parameter affecting its trajectory. During an arc, metal particles are ejected with considerable speed [7]. Observations by Zhu indicate that particles are ejected at an average speed of 10 m/s, with some reaching up to 45 m/s [12]. This variation is attributed to two forces, magnetic and pressure, acting on the particles during the arcing process. Wind directly affects the trajectory length: higher velocities will carry the particles over longer distances [14,16].

The particle size significantly influences their flight trajectories. Due to the dependence of aerodynamic drag on the particle's projected area, smaller particles experience relatively less resistance and are transported farther from their source than larger ones [7,16], as their higher surface-to-volume ratio causes them to cool more rapidly. The work of Tse and Fernandez-Pello highlighted that a particle with lower density is more easily carried by the wind, due to a higher drag-gravity ratio. This means that firebrands will travel greater distances than metals. Similarly, when comparing aluminium and copper, the latter has a higher density, making it reach shorter distances for a given particle size [7].

However, not all the particles will land on the ground. For particles that undergo combustion, such as firebrands, larger particles have an increased likelihood to hit the ground before complete burning, as they take longer to burn due to their size [7,8,10]. On the contrary, particles that are too small will burn entirely in flight [7,9,14]. For a molten particle, the mass and volume remain constant during its flight [7,10].

The temperature evolution of particles during flight is critical, as it determines their temperature upon landing and whether they remain hot enough to ignite the fuel bed. As discussed in Section 1.1, the literature disagrees on whether aluminium particles remain molten or undergo combustion throughout their trajectory. In burning models, the particle diameter changes according to various laws, with surface temperatures exceeding 2000 °C [7,14]. In contrast, molten models determine temperature variations by solving the transient energy equation, accounting for radiative and convective heat transfer [7,16–18].

1.3. Fuel bed ignition

Once ejected, a particle interacts with its surroundings, exchanging heat with the air and the fuel bed upon landing, as shown in Fig. 2. These heat transfer processes can lead to fuel bed ignition, potentially starting a fire. The complexity of the problem arises from the numerous coupled mechanisms, the limited understanding of the thermochemistry within the fuel, and the intricate structure of the fuel bed itself.

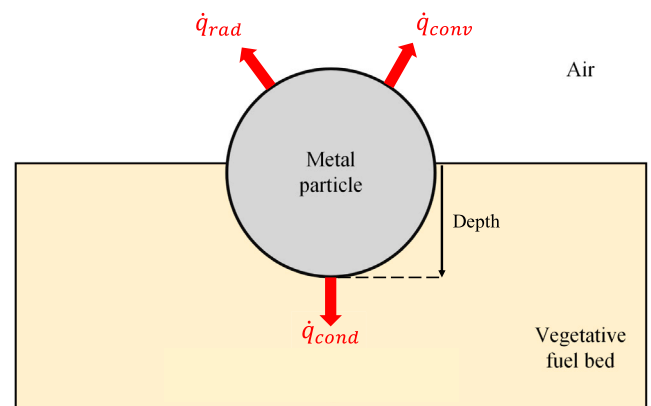


Fig. 2. Schematic illustration of a metal particle embedded in vegetation.

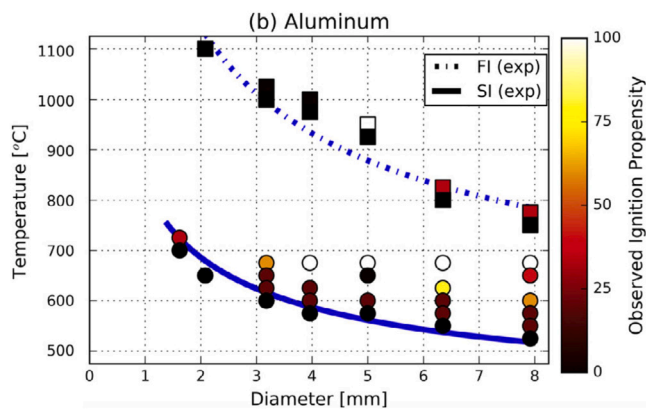


Fig. 3. Figure from Urban et al. [28] of the observed flaming and smouldering ignition boundaries as a function of Aluminium particle's temperature and diameter, for a powdered grass fuel bed.

The majority of available resources on vegetation ignition by hot particles consist of experimental studies. These have observed the flaming and smouldering ignition by metal particles of natural fuel beds [20–22] and cellulosic beds [20,23–26]. The aforementioned experiments are all summarised and compared by Fernandez-Pello et al. [27], where particles with diameters ranging from 2 to 19 mm were heated at temperatures between 500 °C and 1100 °C. These studies primarily focused on flaming ignition. However, Hadden et al. [26], Urban et al. [28] and Wang et al. [29], placed greater emphasis on smouldering. This mode of ignition is particularly important, as it can occur under less restrictive conditions and has the potential to transition into flaming ignition. Moreover, once established, smouldering is more persistent and harder to extinguish than flaming [30,31].

These studies allowed to conclude that the temperature, size and energy of the particle are essential elements to characterise ignition [27]. In particular, studies examining the influence of particle size and temperature on ignition have identified an inverse relationship between these two parameters [22,24–29], as shown in Fig. 3. Specifically, smaller particles require higher initial temperatures to ignite the fuel bed [23,26,27]. It was also observed that the metal type influences the ignition boundaries, with different metals exhibiting distinct relationships between particle size and the temperatures at which ignition occurs [25]. Smouldering ignition occurs at lower particle temperatures and, like flaming ignition, follows a hyperbolic trend [26,28–31]. Fernandez-Pello et al. concluded through experiments that ignition could not be fully determined by the particle's size and temperature, and that a minimal particle energy is required, especially for small particles, for which energy has a greater impact than temperature [23,27]. If the size of the particle increases, a higher energy would be required to ignite the fuel bed [26]. The energy is also directly linked to the chemical state of the metal. Molten particles benefit from the latent heat of melting, which provides additional energy that facilitates ignition of the fuel compared to solid particles at the same temperature. [23,28]. For example, aluminium particles, which have a low melting point, can ignite fuel more easily than steel particles. The effect of melting was observed to be particularly impactful on larger particles [25].

The characteristics of vegetation play a crucial role in understanding its ignition potential. Both experimental observations and theoretical analyses have demonstrated that fuel structure significantly influences ignition propensity. Fuel particle size and density are particularly important: powdered fuels, characterised by smaller size and higher density, require lower temperatures for ignition [20,23,32]. Moreover, biomass fuel composition varies widely, with different types exhibiting distinct ignition behaviours. For instance, when exposed to hot metal particles, alpha-cellulose fuel beds tend to ignite at lower

metal temperatures than biomass fuels, with temperature differences reaching up to 300 °C for larger particles, although the gap narrows as particle size decreases [20]. This phenomenon can be attributed to the complex chemical composition of biomass—including lignin, hemicellulose, proteins, and ash-bearing components that collectively raise ignition temperatures.

Beyond fuel bed structure, moisture content emerges as a critical factor in fuel ignition. Research has shown that ignition becomes impossible above certain fuel moisture contents [32–35]. While previous studies have acknowledged moisture as a key parameter, the depth of understanding remains limited. The research of Manzello et al. for instance, considered only two fuel moisture content levels [36,37], preventing to draw further conclusion. More comprehensive investigations, such as Plucinski's experiments [38], revealed more nuanced insights. Notably, some fuel species with high density demonstrated an absolute resistance to ignition, regardless of how low their moisture content was reduced. These findings suggest that the probability of ignition might decrease with bulk density, indicating that physical characteristics beyond moisture can fundamentally inhibit combustion.

Research on models representing the ignition of vegetation by hot particles, such as firebrands, embers, or metal particles, is notably limited. Hadden et al. [26] applied the hot spot theory [39–42] to model this phenomenon. However, their theoretical results diverged significantly from experimental data, offering only qualitative predictions of ignition behaviour. Zak [23] and Urban et al. [28] investigated numerically the heating of a fuel bed by hot a metal particle to predict smouldering and flaming ignition. While Urban et al. modelled a particle fully embedded within the fuel bed, without free surface, Zak attempted a pseudo-surface interface equivalent. In both cases, the problem was solved using a one-dimensional spherical formulation. This approach implicitly assumes a homogeneous medium all around the particle and doesn't resolve the fuel-air interface, which other studies [5,26] have shown to influence the heat transfer pathways and ignition thresholds. Alternatively, the work of Lautenberger and Fernandez-Pello [43,44] coupled a pyrolysis model with the FDS [45] to take into account both solid and gas phases. The solid phase is modelled using Gpyro, a generalised pyrolysis model introduced by Lautenberger and Fernandez-Pello [46], which allows for the simulation of pyrolysis, heat transfer, and burning of combustible solids. While this study remains the most advanced peer-reviewed work to model vegetation ignition by firebrands, its applicability to hot metal particles has not been investigated. Thus, no existing model today reliably represents the ignition of vegetation by hot metal particles, highlighting a gap in the field.

1.4. Contribution of this work

While models for particle transport and trajectory are relatively well-established, accurate modelling of vegetation ignition upon particle impact remains limited. Moreover, no existing framework combines particle trajectory and vegetation ignition into a unified approach. This study introduces an integrated approach for the ignition of vegetation by hot aluminium particles ejected from power line conductors. It couples the ejection, flight, and interaction of these particles with vegetation, focusing on smouldering ignition, a critical initial phase that precedes and influences the transition to flaming. This method assumes that conductor clashing has occurred, and concentrates on the consequences of this event in terms of particle dispersion and ignition potential. Vegetation ignition is modelled using a pseudo-one-dimensional, physics-based approach implemented in Gpyro, a computational tool based on the generalised pyrolysis model of Lautenberger and Fernandez-Pello [46]. The model is tested in a case study using weather data from Ventura, California, specifically the area affected by the 2017 Thomas Fire, which was ignited by a metal spark from a power line.

2. Particle trajectory model

2.1. Equation of motion

The particle trajectory model is based on the work of Tse and Fernandez-Pello [7], where further details can be found. The particle is subject to two forces as per Eq. (1):

$$m_p \frac{d\vec{v}_p}{dt} = m_p \vec{g} + \frac{1}{2} C_D \rho_{air} A |\vec{v}_R| \vec{v}_R \quad (1)$$

Where $\vec{v}_p = [v_{px}, v_{py}, v_{pz}]$ is the velocity of the particle, m_p its mass, A its surface area. $\vec{v}_R = \vec{U} - \vec{v}_p$ is defined as the relative velocity between the wind and the particle. The air flow is assumed to be horizontal, hence $\vec{U} = U_x \vec{u}_x + U_y \vec{u}_y$. The Stokes number S_k , defined as the ratio of the particle response time to the characteristic time scale of the fluid flow, quantifies the degree to which a particle follows the surrounding fluid motion. For all our simulations conducted, $S_k \sim 1000$, and is therefore significantly greater than 1. Thus, the particles' inertial forces dominate over fluid drag forces, indicating that particle's trajectories will deviate substantially from streamlines. Under these conditions, the effects of turbulent fluctuations on particle motion are negligible and only the average steady wind matters. Moreover, turbulent eddies in the air are at a much greater scale than the particle [7,47], allowing to consider that the particle experiences drag forces in a laminar regime. The expression of the drag coefficient for a smooth sphere is taken from [48]:

$$C_D = \begin{cases} \frac{24}{Re} \left(1 + \frac{3Re}{16}\right)^{0.5} & \text{for } Re \leq 680 \\ 0.4 & \text{for } 680 \leq Re \leq 3 \times 10^5 \end{cases} \quad (2)$$

To account for the effect of the atmospheric boundary layer, Eq. (3) is chosen to model wind speed as a function of height [49]:

$$U = U_{ref} \left(\frac{z}{z_{ref}} \right)^a \quad (3)$$

Where U_{ref} and z_{ref} correspond to reference values, that define the wind speed U_{ref} at a given reference height z_{ref} , that can be chosen arbitrarily. This allows to extrapolate the wind speed at other heights. The roughness of the ground surface is defined by the Hellman exponent a , which characterises how the air flow gradient is evolving with height. In this study, $a = 0.15$ which corresponds to a flat terrain with relatively short grass [49].

2.2. Equations of heat transfer

The literature is divided on whether ejected aluminium particles remain molten and burn mid-flight [7,12,14] or solidify and cool as they travel [16–18]. For this model, the aluminium particle is ejected molten, not burning. The particle's temperature is described by the transient energy equation, given in Eq. (4). The Biot number, defined as $Bi = \frac{h_c d_p}{k_p} \ll 1$, compares the internal thermal conduction resistance to the external convective resistance. Since $Bi \ll 1$ in this case, a lumped capacitance model is appropriate, ensuring a uniform temperature distribution within the particle:

$$m_p c_p \frac{dT_p}{dt} = -A [h_c (T_p - T_\infty) + \sigma \epsilon (T_p^4 - T_\infty^4)] \quad (4)$$

where T_p, c_p are the particle's temperature and specific heat and T_∞ is the ambient temperature. Eq. (4) is initialised with $T_\infty = 25^\circ\text{C}$ and an ejection temperature $T_{p,0} = T_p(t=0) = 1570^\circ\text{C}$, taken from measurements by the State Electricity Commission of Victoria [11]. The average convective heat transfer coefficient h_c is calculated through the Nusselt number, which can be expressed using the correlation of Ranz and Marshall for a sphere [50]:

$$Nu = \frac{h_c d_p}{k_{air}} = 2 + 0.6 Re^{1/2} Pr^{1/3} \quad (5)$$

Table 1

Thermophysical properties of aluminium and air, used to parametrise the particle trajectory model and cooling law.

Property	Symbol	Value	Source
Aluminium			
Density	ρ_p	2380 kg/m ³	[51]
Specific Heat	c_p	1045 J/kg-K	[51]
Thermal Conductivity	k_p	90.7 W/m-K	[27]
Melting Point	T_{melt}	660 °C	[51]
Emissivity	ϵ	0.3	[14]
Air			
Density	ρ_{air}	0.33 kg/m ³	[52]
Specific Heat	c_{air}	1004 J/kg-K	[53]
Thermal Conductivity	k_{air}	0.026 W/m-K	[53]
Dynamic Viscosity	μ_{air}	1.85×10^{-5} kg/m-s	[53]
Kinematic Viscosity	ν_{air}	131×10^{-6} m ² /s	[53]

The values used in the model for aluminium properties are referenced in Table 1. It is important to note that aluminium is ejected at temperatures exceeding its melting point $T_{melt} = 660^\circ\text{C}$ [7]. Consequently, the density value for aluminium used in the model corresponds to that of a molten particle. The simulations run above indicate that particles always land with a temperature above 660°C , justifying the assumption made.

Air properties in Table 1 are considered at atmospheric pressure and at the average between the ambient temperature T_∞ and the particle's ejection temperature, $T_{p,0}$, as explained in more details in [7].

2.3. Statistical approach

Based on Eqs. (1) and (4), a probabilistic model is developed to describe where the particles are likely to land when ejected from the power line. Three key variables are considered to describe the probabilistic landing points: wind, particle ejection speed, and ejection angle. Although particle diameters could follow a probabilistic distribution, a fixed diameter of $d = 6.5$ mm is used to reduce the model complexity and facilitate interpretation. This value falls within the upper range of experimentally observed molten aluminium droplet sizes (e.g., 5 ± 0.5 mm in [13]) and also ensures numerical stability in Gpyro simulations, as further discussed in Section 3.3.

Particle ejection

Following the work of Zhu [12], particles are ejected in specific directions, forming a cone shape aligned with the conductor. Zhu observed that the half-cone angle varied from 30° to 60° . Both the ejection speed and angle are assumed to follow a normal probability law. This is a common assumption made to characterise large samples, which stems from the Central-Limit Theorem [54]. Given that the number of particles ejected when conductors arc is in the order of at least a hundred [8,9,11], the normal distribution approximation is justified.

Three variables are introduced to characterise the particle at the moment of ejection: the ejection speed $V_0 = |\vec{V}_0|$, the angle α between the conductor line and the ejection speed vector $\vec{V}_0$, the angle β between the vertical axis $\vec{u}_z$ and $\vec{V}_0$. These variables are shown in Fig. 4.

Zhu measured the particles' mean ejection velocity varied from 5 to 10 m/s without exceeding 30 m/s [12]. The experiments conducted by the State Electricity Commission of Victoria observed that the particles could reach 16 m/s [15]. Calling x_{V_0} the continuous random variable representing the particle's ejection speed, it follows a normal distribution law, with a mean value $\mu_{V_0} = 15$ m/s and a variance $\sigma_{V_0}^2 = 20$ (m/s)². This allows x_{V_0} to be centred on 15 m/s, and being able to reach maximum values around 30 m/s. To implement this in the numerical model, the continuous normal distribution of x_{V_0} is discretised into 30 equal-width bins between 1 and 30 m/s. This discretisation approach is a commonly used method for approximating

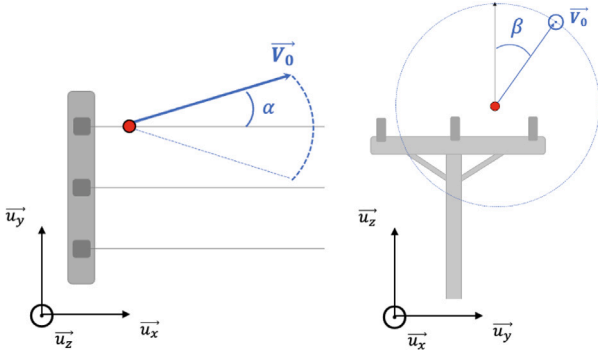


Fig. 4. Characterisation of the particle ejection by the angles α , β and the ejection speed $\bar{V}_0$. The filled circle represents the aluminium particle, as depicted in Fig. 1.

continuous probability distributions in numerical simulations. In this case, it was deemed reasonable to use a bin width of 1 m/s, which ensures a sufficiently fine resolution to capture variation in particle velocity while maintaining computational efficiency.

A discrete variable V_0 is then defined such that $V_0 = v$ if $x_{V_0} \in [v-1, v)$. The representative value of each bin is taken as its upper limit v , a subjective but consistent choice that provides a uniform convention for V_0 . The resulting probability mass function for V_0 is given in Eq. (6), where the probability associated with each bin corresponds to the integral of the continuous probability density function over the interval $[v-1, v)$, with appropriate adjustments at the boundaries.

$$p_{V_0}(n) = \begin{cases} p(n-1 < x_{V_0} < n) & \text{for } n \in \{2, 3, \dots, 29\} \\ p(x_{V_0} < n) & \text{for } n = 1 \\ p(x_{V_0} > n-1) & \text{for } n = 30 \end{cases} \quad (6)$$

A similar approach is followed for the half-cone angle α . Calling x_α the continuous variable representing the angle of the half-cone drawn by the particle's direction of ejection, x_α follows a normal distribution centred on $\mu = 45^\circ$ and of variance $\sigma^2 = 20^{\circ 2}$. This agrees with the aforementioned observations of Zhu [12]. The discrete variable α , representing the half-cone angle, is discretised in intervals of 5° , ranging from 0° to 60° . Eq. (7) follows a similar discretisation method as the one used in Eq. (6) and provides the relationship between α and x_α :

$$p_\alpha(k) = \begin{cases} p(k-2.5 < x_\alpha < k+2.5) & \text{for } k \in \{35, 40, \dots, 55\} \\ p(x_\alpha < k+2.5) & \text{for } k = 30 \\ p(x_\alpha > k-2.5) & \text{for } k = 60 \end{cases} \quad (7)$$

Finally, the angle β is introduced to describe the direction relative to the vertical $\bar{u}_z$ (see Fig. 4). Hence, while α defines the aperture of the cone, β describes the orientation of the spread within the cone. Based on the observations of Zhu [12], β is assumed to follow a uniform distribution between 0° and 360° . To represent this uniform distribution numerically, β is discretised into 64 equally spaced bins over the interval $[0^\circ, 360^\circ]$. This choice of 64 bins is once again deemed reasonable. Each discrete value is associated to a uniform probability of $1/64$.

Wind distribution

Wind speed have a major impact on the particles' trajectory, as they are easily carried away by the air flow due to their small diameter and mass [19]. Wind is characterised by two parameters, its speed and its direction. The wind direction is divided into the 16 directions associated to the compass points (N, NNE, NE, ENE, etc.) and is denoted U_{dir} . The wind speed is classified into 9 ranges according to the

Table 2

Discretisation of wind speeds into bins and associated mean values. The wind is measured at the reference height $z_{ref} = 501$ m. Wind speeds are discretised into intervals following the Beaufort scale, based on observed minima and maxima in the study region. The final bin includes all speeds above 21.15 m/s, which are rarely exceeded in practice.

ΔU_{range} (m/s)	U_{mean} (m/s)
0–1.8	0.9
1.8–3.6	2.7
3.6–5.85	4.7
5.85–8.55	7.2
8.55–11.25	9.9
11.25–14.4	12.8
14.4–17.55	16.0
17.55–21.15	19.4
21.15–	23

Beaufort scale. Table 2 presents these wind speed ranges, denoted as ΔU_{range} , along with their corresponding arithmetic mean speed values, denoted as U_{mean} . The mean wind speeds U_{mean} serve as reference U_{ref} in the vertical wind profile of Eq. (3), allowing adjustment to different heights.

Probability of landing

The set of all possible values taken by the variables $\{(\Delta U_{range}, U_{dir}), V_0, \alpha, \beta\}$ is used to compute the corresponding particle trajectories. For each unique combination of these variables, a trajectory is simulated and its landing coordinates (x_i, y_i) are recorded. Assuming the variables are independent, the probability associated with a given trajectory i , denoted $p(x_i, y_i)$, is calculated as:

$$p(x_i, y_i) = p(\Delta U_{range}^{(i)}, U_{dir}^{(i)}) \cdot p_{V_0}(V_0^{(i)}) \cdot p_\alpha(\alpha^{(i)}) \cdot p_\beta(\beta^{(i)}) \quad (8)$$

2.4. Particle trajectories

The method presented above is used to simulate where particles are likely to land after an arcing event. Wind data is obtained from the RAWS USA Climate Archive [55], using datasets collected from the Wiley Ridge weather station in Ventura County, California, for the year of 2023. Measurements were taken at $z_{ref} = 501$ m above ground. The RAWS dataset provides the relative frequency of occurrence for each paired combination of speed range ΔU_{range} and direction U_{dir} , which defines the probability $p(\Delta U_{range}, U_{dir})$ used in Eq. (8). Fig. 5 shows the wind rose for the sample period, highlighting a wind predominantly coming from two cardinal points.

Eqs. (1) and (4) are solved numerically using Runge–Kutta 45, which is an adaptive time-stepping method for solving ODEs, combining 4th- and 5th-order accuracy. These equations are solved while varying the values of the parameters $\{(\Delta U_{range}, U_{dir}), V_0, \alpha, \beta\}$. As a result, Fig. 6 shows locations where a particle could potentially land, given a particle ejection height of $z_0 = 20$ m. The higher probability of particles landing near the ejection point is primarily due to the generally low wind speeds, as illustrated in Fig. 5.

In terms of temperature, Fig. 7 illustrates the maximum particle temperature at landing obtained from the simulations, at different horizontal distances from the power line, the location of which is represented by the axis $y = 0$. For each location bin, the highest recorded particle temperature is extracted. In other words, for each bin, this means finding T_{max} for all landing points (x_i, y_i) with y_i in the bin. The temperature predictions are shown alongside a smooth curve to highlight overall trend. Fluctuations in the raw data reflect the fact that the model parameters are represented by discrete rather than continuous values. The hottest particles in the line surroundings are approximately 1475°C . At 52 m, which is the maximum distance particles can travel, the temperature drops to approximately 1262°C . Particles travelling greater distances are colder upon landing, which is

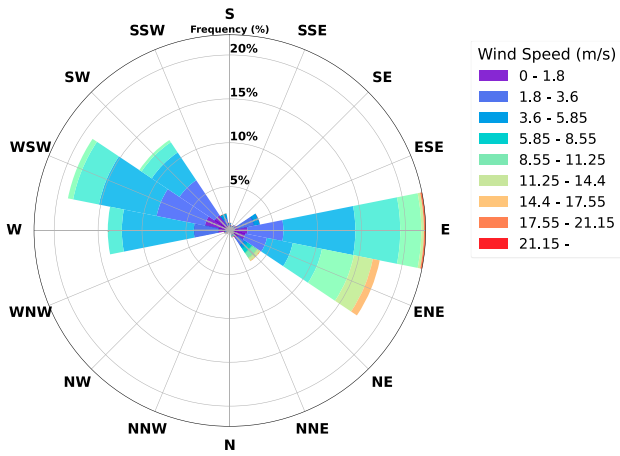


Fig. 5. Wind Rose Diagram, Wiley Ridge - Ventura, California, January 2023–December 2023. Measured at $z_{ref} = 501$ m at the weather station. The wind speed ranges follow the Beaufort Scale.

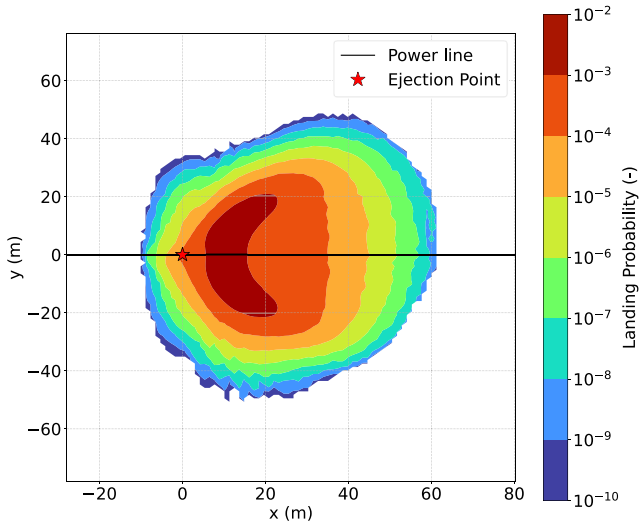


Fig. 6. Probability map of particles landing in the power line surroundings. The ejection point is chosen to be at the origin of the axes, (0,0). Particles are more likely to land close to the ejection point.

attributed to the longer cooling period during their flight. Thus, the hotter particles are found closer to the ejection point. Particle temperature is a key factor, since the likelihood of initiating smouldering ignition depends on the temperature of the particles upon landing, as discussed in the following section. Only particles that are hot enough can ignite the vegetation.

3. Fuel ignition model

3.1. System representation

When the particle reaches the ground, it starts to transfer heat to the vegetation, potentially causing ignition. To model this process, a 1-D geometry is used in Gpyro, which captures the essential mechanisms of vegetation ignition by hot particles while ensuring computational stability. The lumped capacitance method is applied to the metal particle to solve the transient heating problem defined here. Thus, a 0D model is adopted, with $T_p(t)$ the temperature of the particle at any given time t .

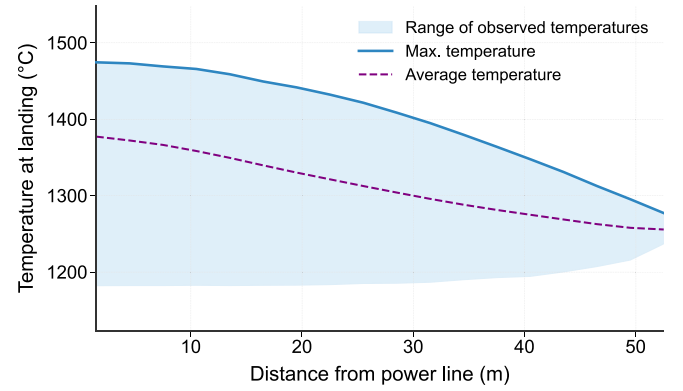


Fig. 7. Particle landing temperature range and average as a function of distance from the power line. Data is binned in 3-m intervals.

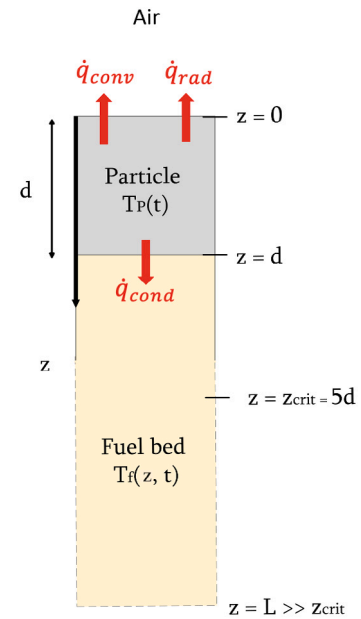


Fig. 8. Pseudo-1D model of the ignition problem. While the vegetation bed is modelled in 1D, the particle is 0D.

The particle is partially embedded in the vegetation bed, as shown in Fig. 2. Through the symmetry along the horizontal axes, the problem can be looked at for only a vertical slice of the two layers, as shown in Fig. 8. The particle exchanges heat with the air in the top half through convection and radiation, while also heating the fuel bed by conduction in the bottom half. This combined setup constitutes a pseudo-1D model: the fuel bed is analysed along a single spatial dimension, yet it remains coupled to the particle, which is represented by a zero-dimensional model.

The ignition phenomenon is analysed into the bed, along the z -axis. The parameter L in Fig. 8 represents the depth of the vegetation bed. The effect of smouldering is studied at a critical depth $z = z_{crit}$, for which it is assumed that if smouldering reaches this point, the particle has the ability to start a wildfire. This is done by choosing a value for z_{crit} significantly larger than the particle's diameter, ensuring that the smouldering front travels far enough to consider that there is a fire risk. In this report, its value is taken as $z_{crit} = 5d$, and $L = 10z_{crit}$, ensuring that the bed is semi-infinite through $z_{crit} \ll L$.

Table 3

Reaction parameters for the fuel bed smouldering ignition, used in Gpyro.

Reaction	Z (s ⁻¹)	E (kJ/mol)	ΔH (MJ/kg)
R1	4500 [60]	43.9 [60]	2.4 [60]
R2	1.21 × 10 ¹⁴ [57]	190.4 [57]	0.37 [57]
R3	5.60 × 10 ⁹ [61]	160 [61]	-25 [61]

Table 4

Chemical properties of the species in the vegetation bed and smouldering ignition, used in Gpyro.

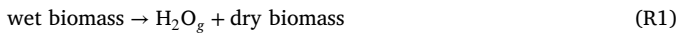
Species	ρ (kg/m ³)	k (W/m-K)	c (J/kg-K)	ε (-)	ρ _s (kg/m ³)
Dry Biomass	1.70 [59]	0.126 [62]	2300 [62]	0.94 [63]	513 [59]
Char	0.60 ^a [56]	0.2 [64]	1100 [62]	0.95 [56]	180 ^a [56]
Ash	0.017 ^a [56]	0.8 [64]	880 [64]	0.95 [65]	5.13 ^a [56]

^a The density of char and ash are calculated from the density of the biomass: $\rho_{char} = 0.35\rho_b$ and $\rho_{ash} = 0.01\rho_b$.

3.2. Chemical reactions

Smouldering ignition, which is the focus of this model, represents the initial stage of ignition observed for small hot particles, similar to that occurring with firebrands before the onset of flaming [30]. Focusing on smouldering ignition enables the model to examine the critical initial phase that constitutes the stepping stone for subsequent flaming.

The process of smouldering ignition of the fuel bed is modelled through 3 chemical reactions: drying, pyrolysis and char oxidation. The vegetation bed is referred to as *biomass*, while *pyrolysate* refers to the gas produced during pyrolysis [31]. The chemical reactions are the following:



The drying model (R1) and its pyrolysis (R2) are taken from Richter et al. [56,57]. These proved that the simplest scheme is the accurate enough to predict wood pyrolysis in fire models [57]. Thus, a single-step Antal scheme [58] was chosen for this study, associated with reaction (R2).

The parameters of the 3 reactions implied in the chemical model are shown in Table 3. Following the nomenclature used by Lautenberger and Fernandez-Pello in [44], Z and E are respectively the pre-exponential factor and the activation energy in Arrhenius law, and ΔH is the heat of reaction. The properties of each species are available in Table 4. The vegetation used in this work is characterised using the Scott and Burgan fuel behaviour model [59]. The fuel bed was assumed to be a GS2 fuel, a mixture of grass and shrub typically found in the Ventura region. The Scott and Burgan model provided both the density and packing ratio for each type of fuel. To determine the density of each fuel, only the fine fuel loads – which encompass 1-hr fuels and live herbaceous and woody – are considered. This allowed to calculate $\rho_b = 1.7 \text{ kg/m}^3$ and $\rho_{s,b} = 513 \text{ kg/m}^3$.

The reactions (R1), (R2) and (R3) are simulated on Gpyro, an open-source simulation tool allowing to model pyrolysis and smouldering for condensed-phase materials [44]. It solves a set of coupled equations for the conservation of gaseous and condensed-phase mass, species, energy and gas phase momentum. Gpyro requires the definition of a mesh, for which a sensitivity analysis was conducted to determine an appropriate resolution. Simulations were performed with varying numbers of cells: $n_{cells} = 50, 100, 500, 1000, 2000$ and 3000. For n_{cells} between 500 and 3000, the simulation results were nearly identical, with a variation

in values of approximately ± 6% for the reaction rate of the char oxidation. This corresponds to a less than 1% variation for the critical particle temperature required for ignition. Based on this analysis, a 500-cell mesh was selected, corresponding to a resolution of 0.2 mm, as it provides a balance between the accuracy of the result and the computational efficiency. The following section presents the boundary conditions used in the simulations.

3.3. Boundary conditions

At the interface between the particle and the fuel bed, the vegetation is directly in contact with the particle. Boundary conditions are imposed to ensure continuity of temperature, species transport, and pressure between the particle and the porous domain:

$$\begin{cases} T(z = d, t) = T_p(t) \\ -\Phi \rho_g D \frac{\partial Y_j}{\partial z} \Big|_{z=d} = h_{m,z=d} (Y_j^\infty - Y_{j,z=d}) \\ P_0 = P_\infty \end{cases} \quad (9)$$

At the deep boundary, the vegetation is assumed to be sufficiently thick, with $L \gg z_{crit}$, allowing heat and mass to propagate inward. Heat conducted through the medium is balanced by convective and radiative losses at this boundary:

$$\begin{cases} -k \frac{\partial T}{\partial z} \Big|_{z=L} = -h_c (T_{z=L} - T_\infty) - \epsilon \sigma (T_{z=L}^4 - T_\infty^4) \\ -\Phi \rho_g D \frac{\partial Y_j}{\partial z} \Big|_{z=L} = h_{m,z=L} (Y_j^\infty - Y_{j,z=L}) \\ P_0 = P_\infty \end{cases} \quad (10)$$

Where j refers to the index of the gas and T_p is the particle's temperature. The heat transfer coefficient is estimated at $h_c = 12.5 \text{ W/m}^2 \text{ K}$ and $h_{m,z=d} = h_{m,z=L} = 0.01 \text{ kg/m}^2 \text{ s}$ [56].

The evolution of the particle temperature T_p is described using a lumped heat transfer model, which accounts for the exchange of heat between the particle and its surroundings. As shown in Fig. 8, the particle loses heat to the vegetation and to the air:

$$\frac{m_p c_p}{A_p} \frac{dT_p}{dt} = -\epsilon \sigma (T_p^4 - T_\infty^4) - k_p \frac{\partial T}{\partial z} \Big|_{z=d} - h_{c,air} (T_p - T_\infty) \quad (11)$$

where $A_p = \frac{1}{2} 4\pi r^2$ corresponds to the bottom half of the particle that is embedded in the vegetation bed, which is also equal to the surface in contact with the air. The effective thermal conductivity k_p is suited for porous media and accounts for the voids in the fuel bed:

$$k_p = (1 - \phi)k_v + \phi k_{air} \quad (12)$$

where k_v and k_{air} are respectively the thermal conductivity of the vegetation and the air, and ϕ is the porosity of the fuel. The numerical results revealed that only radiative and convective heat transfer between the particle and the vegetation bed significantly influenced the particle cooling (Eq. (11)), while the conductive heat transfer between the particle and the fuel bed was found to have a negligible impact. This low value reflects the sparse vegetation considered in this study.

Since the model is pseudo-1D, the particle temperature evolution was computed by solving Eq. (11) using the LSODA ODE solver [66] implemented in Python. This provides discrete values of $T_p(t)$ at selected times, which are then applied as a time-varying boundary condition at the particle-fuel bed interface in Gpyro, as described in Eq. (9). Particle size significantly influences thermal behaviour: smaller particles ($d = 1\text{--}2 \text{ mm}$) have a higher surface-to-volume ratio, which leads to faster cooling. This rapid temperature drop results in stiff boundary conditions, varying too quickly for Gpyro's solver and was observed to often cause the simulation to diverge. Accordingly, a larger particle diameter was selected, as introduced previously. The smallest value found to consistently yield stable simulations was $d = 6.5 \text{ mm}$, which remains within the range of observed particle diameters discussed in Section 1.1.

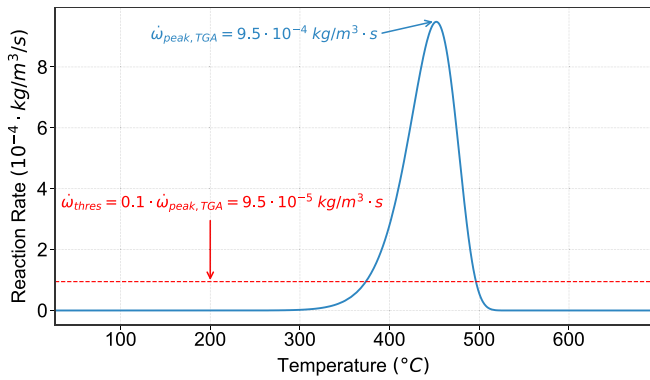


Fig. 9. Predicted reaction rate as a function of temperature in the TGA simulation of char oxidation. The reaction rate threshold is defined as 10% of the peak value of the TGA curve.

3.4. Probability of vegetation ignition

Ignition is evaluated by examining the rate of char oxidation (R3), using a critical reaction rate threshold $\dot{\omega}_{thres}$. If the reaction rate surpasses this threshold $\dot{\omega}_{ox} > \dot{\omega}_{thres}$, the ignition is considered robust enough to continue spreading. As previously introduced, the reaction rate is evaluated at a distance $z_{crit} = 5d$ from the particle (see Fig. 8), which serves as an indicator of the reaction's ability to propagate beyond its initial ejection point.

The reaction rate threshold is determined by simulating on Gpyro a TGA experiment of biomass reactions, in air atmosphere. TGA is used to identify values for kinetic constants in pyrolysis [61,67]. This approach ensures that the ignition criterion is based on the chemical reaction progress rather than solely on temperature. While temperature is a key factor for ignition, the oxidation reaction (R3) also depends on oxygen availability in the vegetation bed. Consequently, using a reaction rate threshold accounts for both temperature and oxygen concentration. The initial temperature is 300 K and the heating rate is 10 °C/min. From this, the reaction rate as a function of temperature is obtained (see Fig. 9). The reaction rate threshold for the model is chosen by taking 10% of the curve's peak value $\dot{\omega}_{peak}$, resulting in $\dot{\omega}_{thres} = 9.5 \cdot 10^{-5} \text{ kg/m}^3 \cdot \text{s}$. The associated probability of smouldering ignition χ_{ox} takes either the value 1 if smouldering is considered to be sustained with $\dot{\omega}_{ox} > \dot{\omega}_{thres}$, and 0 if not. The value of $\dot{\omega}_{ox}$ is directly influenced by the temperature T_{land} of the particle when it lands.

The probability of vegetation ignition at a given point is calculated by combining the results presented above with those of Section 2.3. For each trajectory, the temperature of the particle when it reaches the ground is calculated, and used in Eq. (11) to establish the boundary conditions for Gpyro. Subsequent simulations allow to assess whether the particle is hot enough to ignite the fuel bed, based on the previously defined ignition threshold $\dot{\omega}_{thres}$ and allows to calculate $\chi_{ox,i}$ for each particle trajectory and landing temperature. The probability of smouldering of the fuel bed and the particle landing point are assumed to be independent, leading to the final probability $p_{fire,i}$ that a particle might lead to ignition at a point (x_i, y_i) :

$$p_{fire,i} = p(x_i, y_i) \cdot \chi_{ox,i} \quad (13)$$

3.5. Fuel ignition predictions

The fuel moisture content is obtained through a dataset provided by the National Center for Atmospheric Research [68]. This allowed to choose an average moisture content of 10% for the simulations.

The simulations conducted on Gpyro allowed to determine that for the chosen vegetation bed, the critical temperature above which

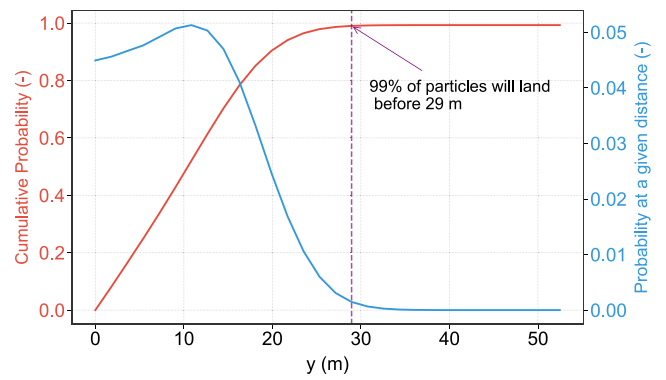


Fig. 10. Cumulative probability of smouldering ignition occurring within a given distance from the power line, along with probability of smouldering ignition at a given distance.

$\dot{\omega}_{ox} > \dot{\omega}_{thres}$ is approximately $T_{crit} = 740 \text{ °C}$, assuming sufficient oxygen availability throughout the bed depth. As shown in Fig. 7, all the particles generated land on the ground exceeding the critical temperature. This result is expected, given that particles are ejected at 1570 °C , well above the threshold. The subsequent cooling is therefore insufficient to reduce their temperature below 740 °C , leading to $\chi_{ox,i} = 1$ in all cases. This outcome depends on the specific input parameters, such as particle ejection temperature and fuel bed characteristics. Under different conditions, $\chi_{ox,i}$ may take other values.

Consequently, for aluminium particles of 6.5 mm in diameter ejected from $z_0 = 20 \text{ m}$, smouldering ignition is likely to start at any points at which particles land, as shown in Fig. 6. The critical particle temperature identified can be compared to previous experiments led of vegetation ignition by aluminium particles. Urban et al. [20] measured a threshold temperature of 900 °C for grass blend ($\rho = 57 \text{ kg/m}^3$) and 855 °C for pine needles ($\rho = 75 \text{ kg/m}^3$). These temperatures are higher than the 740 °C identified in the model for a grass-shrub mix. However, Urban et al.'s results pertain to flaming ignition, which requires higher temperatures than smouldering.

Particles can travel up to 52 m from the power line, with an at-risk zone of 274 m^2 where smouldering may be initiated. The at-risk zone (or at-risk area) refers to the region where particles can land and ignite the fuel bed. It is determined by computing the convex hull of the points that satisfy Eq. (13). Fig. 10 shows the cumulative probability of smouldering ignition occurring within a given distance from the power line, along with the associated probability of ignition at a given distance from the power line. Fig. 10 is derived from the set of landing points presented in Fig. 6. The power line is positioned along $y = 0$, and distances are measured perpendicularly from this line along the y -axis. The probability of smouldering ignition occurring within a given distance y from the power line is obtained by summing the ignition probabilities $p_{fire,i}$ of all landing points $P_i(x_i, y_i)$ that fall within the range $-y < y_i < y$. While particles can travel up to 52 m away from the power line, 99% of ignition scenarios result in particles landing within 29 m, indicating a strong spatial concentration of risk near the source.

Fig. 10 highlights that there is a 50% chance that smouldering ignition starts within 12-m away from the power line. For comparison, Californian electric utilities trim vegetation around power lines within 3 m of poles and towers [69]. Most clearance strategies are designed to prevent contact between conductors and trees or branches; however, they do not account for the potential generation and ejection of hot metal particles. Moreover, it can be noted that the most probable landing point area is around 10 m away from the power line.

4. Sensitivity analysis

A sensitivity analysis is conducted to examine how the variation of several parameters affects the probability of smouldering ignition. The four parameters assessed are wind speed, fuel moisture content, reaction rate threshold and conductors' height.

Wind impacts particle behaviour in two opposing ways. On the one hand, it carries particles farther away from the power line. On the other, it accelerates cooling through the convective heat transfer coefficient (see Eq. (5)), potentially offsetting the effect on distance. To assess how wind influences the overall fire risk, three unidirectional wind scenarios are considered: aligned with the particle ejection direction, opposed to it, and perpendicular to it. It differs from what has been defined in Fig. 5, where the wind distribution was probabilistic. Fig. 11 illustrates the aforementioned and shows particle landing points for a wind of 10 m/s in the three directions.

For the sensitivity analysis, the wind speed is considered within a range of 0 to 50 m/s, allowing to consider both quiescent conditions and extreme wind. Fig. 12(a) shows the maximum distance from the power line at which smouldering can start, as well as the at-risk area, as a function of wind speed and direction. Wind blowing perpendicular to the power line leads particles to reach greater distances from the conductors, doubling from approximately 40 m at 0 m/s to 80 m at 30 m/s, and even reaching 110 m at 50 m/s. When the wind is aligned with the ejection direction, the maximum distance travelled is relatively constant over the various wind speeds, and slightly decreases when the wind is opposite. This highlights that wind becomes most threatening when it blows perpendicular to the power line, as it will contribute to conductors swinging and clashing, while also allowing particles to land farther from the power line than in other scenarios. Nevertheless, the at-risk area significantly increases with wind speed when the wind is aligned with the ejection direction, from 195 m² at 0 m/s to 300 m² at 50 m/s. This can be attributed to the wind reinforcing the particles' initial momentum, extending their trajectories and elongating the at-risk area. At each wind speed and wind direction investigated, the particles maintained temperatures at landing above approximately 1180 °C, exceeding $T_{crit} = 740$ °C in any case. Thus, all particles ejected are hot enough to initiate smouldering ignition when landing on the fuel bed, regardless of wind speed and direction. Consequently, the potential cooling of wind is overshadowed by the significant extension of particle travelled distances and at-risk areas.

The effect of the height of ejection is then assessed. Power line heights vary depending on their voltage level, purpose, and surrounding environment. Distribution lines are generally lower, while high-voltage transmission lines can reach significant heights. To account for this variability, eight different ejection heights were examined, ranging from 5 m to 40 m, which align with common power line heights found in practice. The results shown in Fig. 12(b) indicate a nearly linear increase in both the maximum horizontal distance travelled by the particles and the corresponding at-risk area as the ejection height increases. This behaviour is expected, as a greater ejection height provides particles with more time to travel before reaching the ground. In the absence of significant aerodynamic forces acting to decelerate the particles, the vertical motion remains dominated by gravity, leading to a direct proportionality between ejection height and travel time. Consequently, higher ejection heights allow particles to disperse over a wider area, increasing the spatial extent of potential fire ignition zones.

A clear decreasing trend is observed in both maximum and minimum landing temperatures with increasing ejection height (see Fig. 13). This trend can be attributed to the longer cooling during flight. Notably, the maximum landing temperature decreases at a slightly higher rate than the minimum landing temperature. This can be explained by the stronger impact of radiative heat transfer at high particle temperature, that contributes to a sharper particle cooling.

The reduction in landing temperature with ejection height has important implications for wildfire ignition potential. While the overall

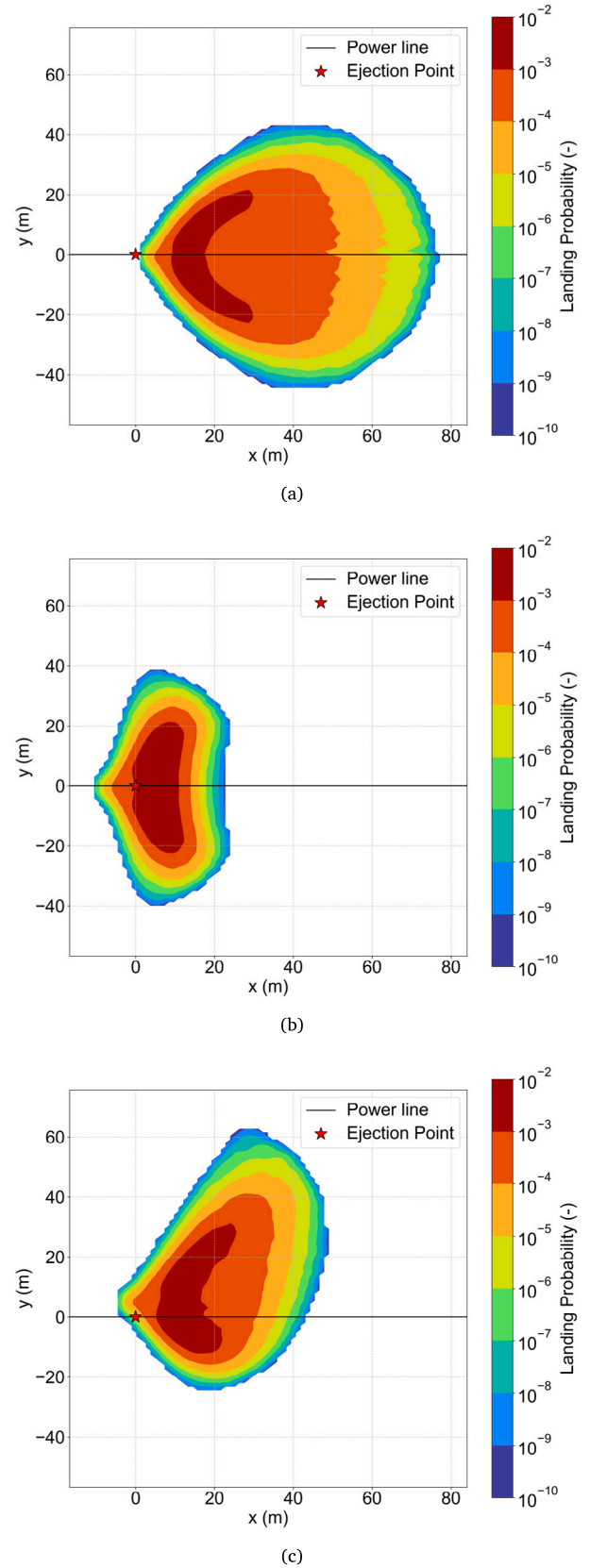


Fig. 11. Simulations of particle landing points with a unidirectional wind at 10 m/s (a) aligned, (b) opposed and (c) perpendicular to the ejection direction.

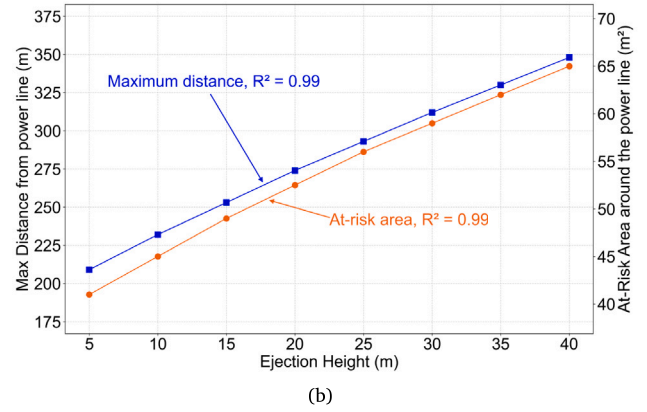
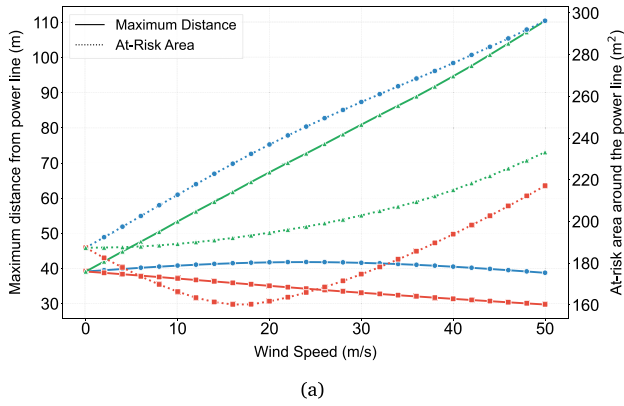


Fig. 12. Effect of (a) of wind speed and alignment and (b) ejection height on the maximum distance from the power line where smouldering can start and the at-risk area.

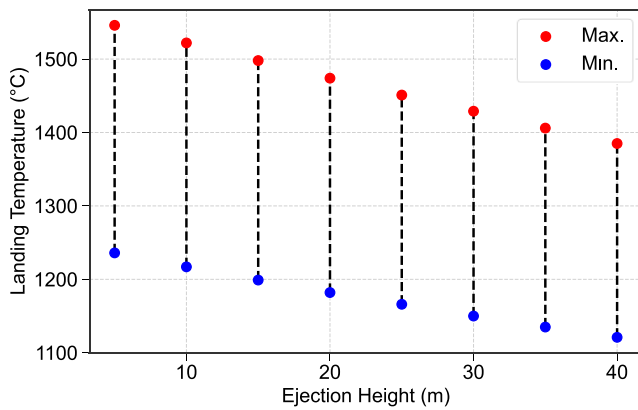


Fig. 13. Landing temperature range as a function of particle's ejection height. The range remains constant, but both the minimum and maximum values decrease linearly.

probability of ignition remains very likely in the different simulations, lower landing temperatures could be below the ignition thresholds for other types of vegetation and moisture conditions. Further studies could explore whether specific vegetation types become less susceptible to ignition as ejection height increases.

The findings suggest that power line height directly influences the distance over which fire can be initiated with particle ignition. While 6.5 mm aluminium particles ejected from higher power lines land at lower average temperatures, they remain hot enough to ignite the fuel bed, while their increased ejection height leads to larger at-risk areas.

The fuel moisture content (MC) plays a critical role in determining ignition propensity. As seen in Section 3.2, the drying reaction (Eq. (R1)) has a lower activation energy compared to the other reactions, and thus initiates first. Acting as a heat sink, the drying reaction absorbs energy that would otherwise contribute to increasing the temperature of the fuel, reducing the energy available for subsequent reactions. The amount of heat required to fully dry the fuel varies depending on its moisture content; higher moisture levels demand more energy to achieve complete drying, directly impacting the ignition process [70]. The model is run for 8 different moisture contents, ranging from 2% to 100%, while the other parameters are held constant. Fig. 14 shows the critical particle temperature at landing needed to lead to smouldering, as a function of the moisture content.

The results show that there is a strong linear correlation between the moisture content and the minimum temperature required to initiate smouldering. The critical temperature varies from 720 °C for the lower

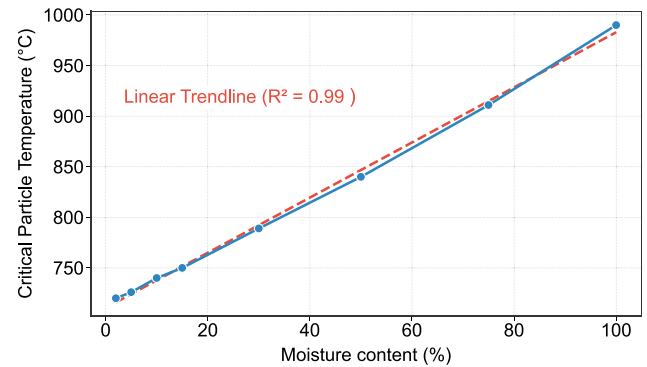


Fig. 14. Minimum temperature of the particle at landing required to sustain smouldering, as a function of the fuel moisture content.

moisture content tested, to 990 °C for the highest one. This wide range of temperature highlights how the drying process acts as a heat sink. Similar to the wind sensitivity analysis, the temperature values in Fig. 14 are well below those at which particles typically land on the ground, making smouldering ignition highly likely in all moisture content scenarios.

The impact of the reaction rate threshold on the critical particle temperature for vegetation smouldering was evaluated. As established previously, the reaction threshold in this model corresponds to 10% of the peak value of the TGA curve (see Fig. 9), associated with the char oxidation reaction. The model's response was examined by modifying the threshold across different percentages of the TGA curve peak. Fig. 15 shows the critical particle temperatures identified for each threshold from 1% to 100% of $\dot{\omega}_{peak}$.

The sensitivity analysis shows a non-linear relationship between the reaction rate threshold and the critical particle temperature in the model. At lower thresholds ($0.01\dot{\omega}_{peak}$ to $0.2\dot{\omega}_{peak}$), the critical temperature changes rapidly, with an 20 °C increase between $0.01\dot{\omega}_{peak}$ and $0.05\dot{\omega}_{peak}$. This part of the curve is highly sensitive, where small threshold changes cause large temperature shifts. As the threshold rises above $0.2\dot{\omega}_{peak}$, the temperature increases more softly. The chosen threshold of $0.1\dot{\omega}_{peak}$ results in a critical temperature of 740 °C, which is closer to the lower end of the temperature range shown in Fig. 15. This indicates that the chosen reaction rate threshold lies in the steep region of the curve, where small variations in the threshold result in relatively large changes in the predicted ignition temperature. A total variation of 163 °C is observed between the lowest and highest thresholds tested. Such a wide range indicates significant uncertainty in predicting the critical particle temperature and emphasises the model's sensitivity to the reaction rate threshold selection.

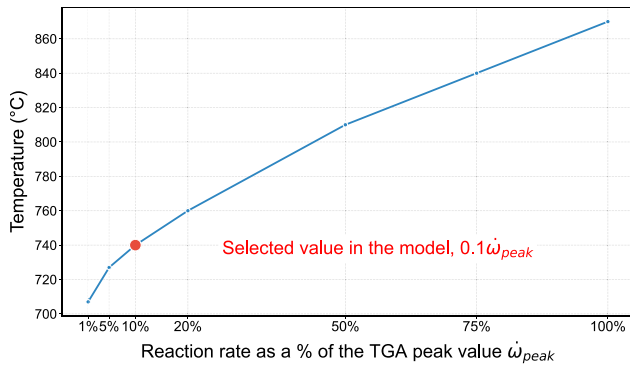


Fig. 15. Critical particle temperature for smouldering ignition for different reaction rate thresholds. The thresholds are defined as a percentage of the peak reaction rate value obtained in TGA conditions, shown in Fig. 9.

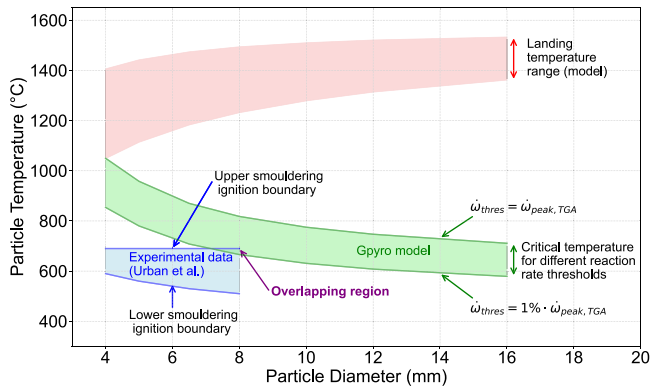


Fig. 16. Effect of particle diameter on the critical landing temperature required for smouldering ignition of the fuel bed obtained with the model. These results are compared to the experimental data of Urban et al. [28]. The figure also shows the landing temperature ranges for each diameter obtained with the model.

The particle diameter influences its thermal behaviour, particularly the rate of heat loss during flight and heat transfer upon contact with the vegetation, as mentioned in Section 1. To assess the influence of particle size on the ignition outcome, simulations are conducted for various aluminium particle diameters, ranging from 4 to 16 mm. For each particle diameter, the critical temperature for vegetation ignition is determined and shown in Fig. 16. Since the reaction rate threshold governs the ignition criterion itself, the critical temperature is determined for different particle diameters using the lower and upper reaction rate thresholds studied in Fig. 15, respectively $\dot{\omega}_{thres} = 0.01\dot{\omega}_{peak}$ and $\dot{\omega}_{thres} = \dot{\omega}_{peak}$. This provides a critical temperature envelope, that reflects the range of temperatures at which ignition is predicted to occur.

Smaller particles, such as those with a diameter of 4 mm, require higher temperatures (893 °C) to ignite the vegetation, compared to 740 °C in the base case. Conversely, larger particles ignite at lower temperatures, with the ignition threshold stabilising for diameters above 10 mm. Fig. 16 was obtained using aluminium particles falling onto a fuel bed with properties detailed in Table 4. These results demonstrate that particle diameter significantly influences ignition likelihood at small scales. Overall, the relationship between particle diameter and temperature shown in Fig. 16 is hyperbolic, as reported in the literature (Section 1.3). In particular, the results obtained with Gpyro are compared with experimental data of Urban et al. [28] (Fig. 3). Despite differences in fuel and particle properties, the Gpyro predictions align with the experimental data from [28] for particles larger than 7 mm. Although the experimental data only extends to 8 mm, the observed trend

suggests this agreement would likely continue for larger diameters. This consistency supports the model's validity in predicting ignition behaviour for larger particles; however, further data are needed to fully confirm the model beyond this size range.

Fig. 16 illustrates the landing temperature ranges of aluminium particles of different diameters, obtained through simulations. This study focuses on 6.5 mm particles, yet the literature shows that most particles are smaller, often around 1–2 mm in diameter [8–10]. Previous work has typically treated flight and ignition separately: particles were dropped directly onto the fuel bed to determine the critical temperature for smouldering ignition [26,28,29]. In contrast, here both processes are coupled by accounting for the cooling of particles during flight after ejection. Fig. 16 therefore compares, for each diameter, the landing temperature range with the critical temperature required for smouldering ignition, depending on the reaction rate threshold. These results have been obtained using the flight path and fuel bed ignition model introduced in this work. In all cases, particles reach the vegetation surface at temperatures significantly exceeding the smouldering ignition threshold. However, as particle diameter decreases, the landing temperature range approaches the critical ignition temperature, and both begin to overlap at around 4 mm. This trend suggests that for particles smaller than 4 mm, not all of them may retain sufficient heat to initiate smouldering ignition upon contact, as their higher surface-to-volume ratio enhances convective and radiative cooling during descent. Although such small particles are more frequently generated, their rapid cooling and the need for higher landing temperatures to achieve ignition considerably reduce their likelihood of igniting the fuel bed. Larger particles, such as the 6.5 mm case studied here, are more likely to remain above the ignition threshold by the time they reach the surface. This suggests that, despite their lower frequency, larger particles may represent a greater ignition risk than the smaller but more abundant ones. Future work should further investigate this balance by coupling particle size distributions with ignition probability, in order to determine ignition risk across the full range of particle sizes.

5. Conclusion

Power lines can initiate wildfires, and increasing attention is needed as this issue continues to grow [71]. This study provides a probabilistic model for predicting the smouldering ignition of vegetation caused by hot metal particles ejected by power line arcing. The model assumes that conductor clashing has occurred and focuses on the consequences of such an event. It integrates sub-models for particle ejection, trajectory, and temperature evolution, and uses a pseudo-one-dimensional approach to simulate the smouldering ignition of vegetation caused by metal particles. The findings indicate that key parameters, including power line height, wind direction and speed, particle ejection speed and direction, and fuel moisture content, critically influence ignition probabilities and the area where particles can land.

The model was run for 6.5 mm aluminium particles, using weather data from California, known for the 2017 Thomas wildfire that was initiated by metal sparks ejected from a power line. Particles landing near the power line are hotter due to limited air flow cooling. Particles capable of initiating smouldering ignition can travel up to 52 m from the power line, resulting in a 274 m² at-risk zone around the point of conductors clashing, and a guaranteed smouldering ignition upon spark generation and ejection. After an arcing event, there is a 50% likelihood of smouldering ignition occurring within 12 m of the power line. The simulations on Gpyro allowed to determine that 6.5 mm aluminium particles would require to be at approximately 740 °C to ignite the chosen fuel bed, a mix of grass and shrub, particularly sparse.

Sensitivity analyses highlighted that wind mostly affects particle's trajectories. However, its cooling effect was found to have no significant impact on the likelihood of smouldering ignition, under the conditions of the simulations. This is due to the significant temperature difference between the particle upon landing and the critical ignition

temperature required for smouldering. While winds opposed to the ejection direction represent a minor threat, winds perpendicular to the ejection contribute to particles landing further away from the power line, with the distance travelled doubling from 40 m to 80 m when wind speed increases from 0 to 30 m/s. On the other hand, high winds aligned with the ejection direction enhance the initial motion of the particle. This results in wider at-risk area, which increase approximately linearly from 195 m² at wind speed of 0 m/s to 300 m² at 50 m/s.

The moisture content of the fuel impacts the ignition primarily by modulating the smouldering threshold. In the simulations conducted, the smouldering temperature threshold increased proportionally with the moisture content, with critical particle temperatures ranging from 720 °C to 990 °C for the moisture content values considered.

The sensitivity analysis of reaction rate thresholds reveals that small changes at lower thresholds cause significant shifts in critical temperature. The chosen threshold in the model lies in a sensitive region, indicating that careful consideration is needed when selecting threshold values.

Depending on the height at which particles are ejected, particles will be able to travel greater distances. For the ejection heights considered, particles could reach approximately 40 m for a low, 5 m-high power line, against 65 m for higher conductors at a height of 40 m. Particles ejected from higher power lines would also reach the ground at lower temperatures due to an increased flight time, enhancing their cooling.

The influence of particle diameter was also investigated. A hyperbolic relationship was observed between diameter and the critical ignition temperature: smaller particles need higher temperatures to initiate smouldering, with 4 mm particles igniting at 893 °C compared to 740 °C for 6.5 mm particles. Larger particles ignite at lower temperatures, with the threshold stabilising above 10 mm. For particles above approximately 7 mm, the model predictions align well with existing experimental data, supporting its validity for larger diameters. However, smaller particles cool more rapidly in flight, making them less likely to retain enough heat to reach ignition temperatures upon landing. This highlights the dual role of particle size in both thermal inertia and ignition potential.

The model offers valuable insights into the mechanisms underlying smouldering ignition from power line faults, enhancing the understanding of fire risks associated with infrastructure failures. The methodology and findings lay a pathway for future research to improve risk prediction and inform fire prevention strategies.

CRediT authorship contribution statement

Auriane Javaloyes: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alexander Castagna:** Writing – review & editing, Supervision, Software, Methodology. **Nikolaos Kalogeropoulos:** Visualization, Supervision, Methodology. **Guillermo Rein:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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