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Development of wildland fire exposure indicator for performance-based design applications

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Abstract

Fire curves provide a simplified yet practical and operational description of a fire over time, and are widely used in engineering applications for building design and risk assessment. They are generally fit for deterministic performance-based applications, where a quantitative description of the reasonable level of hazard associated with the fire is compared against performance metrics to assess the suitability of a particular design. Although the use of fire curves in performance-based applications is now well established for urban developments, its use in the context of wildland-urban interface (WUI) building design remains in its infancy. This paper presents a new fire curve, here referred to as wildfire curve, suitable for applications in the WUI. The curve was derived from more than 20.000 brightness temperature measurement locations acquired during a 150 x 200 m2 prescribed gorse shrub burn using Unmanned Aerial Vehicles (UAV) technology, and 25 in-situ temperature probes evenly spaced inside the experimental plot. The measurements were linked to its local behaviour using an overhead visual video footage and Light-Detection-and-Ranging (LiDAR) data of the vegetation canopy. Furthermore, this paper proposes and discusses a methodology to estimate heat release rate from the proposed wildfire curve, enabling more comprehensive fire engineering design and risk assessment applications.

Keywords: wildfire, resilience, wildland-urban interface, WUI, rural-urban interface, RUI, design, performance-based design, performance solution, verification, verification methods, wildfire engineering, fire safety engineering, fire engineering, urban planning.

1. INTRODUCTION

Wildfires raging at the wildland-urban interface (WUI) devastate homes and communities, posing a global threat (Filkov et al., 2020). Despite a long history of harnessing fire and incorporating fire safety principles into urban design, WUI mitigation strategies remain underdeveloped. These strategies vary considerably by country and lack methods to assess designs that deviate from building code requirements, known as "alternative" or "performance-based design" solutions (Penney et al., 2024).

Performance-based design (PBD) has become a well-established approach for fire safety in urban building design, with inclusion in various international regulations (Australian Building Codes Board (ABCB), 2021) and guidelines (Society of Fire Protection Engineers (SFPE), 2015). Unlike prescriptive methods, PBD offers a step-by-step process allowing designers to address a building's unique features and uses. This inherently fosters a deeper understanding of how the building will perform in a fire event (Hurley & Rosenbaum, 2015). Consequently, PBD is often the preferred choice for projects requiring flexibility, such as those exceeding the scope of prescriptive regulations or where cost-optimization is a priority.

Wildfire engineering currently offers limited application of PBD. Existing codes include it only in specific, optional clauses where flexibility is needed. These decisions often rely on expert judgment rather than a rigorous wildfire engineering framework built on first principles. This limitation has spurred research efforts to explore PBD's applicability in WUI fire scenarios. For example, Vacca et al. (Vacca et al., 2020) proposed a framework utilizing advanced computational tools to quantify fire exposure in specific design scenarios. They further proposed evaluation methods based on PBD goals, focusing on building vulnerability in Southern European WUI regions.

PBD hinges on quantifying the potential fire hazard a building will face. This allows for evaluating design suitability and selecting features that minimize risk to acceptable levels. There are two key aspects to this quantification. The first is the Building Performance Criteria which defines specific performance thresholds and determines the acceptable limits for the design. These could be related to structural integrity, heat resistance, or occupant safety during a fire event. The second is the Level of Hazard which involves quantification of fire hazard typically via the definition of a design fire curve. This curve describes the expected fire intensity over time, offering an engineering measure of potential harm. While established design fire curves exist for urban fires, derived from controlled experiments and based on factors like heat release rate or temperature, these are unsuitable for WUI applications. This is because wildfire behaviour, occupant behaviour, protection strategies, and firefighting capabilities differ significantly between urban and wildland settings.

Our review indicates that the design fire curve proposed by Cantor et al. (Cantor et al., 2022) is currently the only option for WUI applications. However, it has limitations. Firstly, the underlying model by Blagojević and Pešić (Blagojević & Pešić, 2011) was originally designed for compartment fires in urban environments, not the open wildfires of the WUI. Secondly, the curve relied on a limited set of experimental data from crown and shrubland fires. Finally, the curve lacks a clear connection to the unique characteristics of wildfires. Therefore, a meticulously defined WUI design curve is needed. This curve should be specifically developed for wildland fires, capture the distinct stages of a wildfire, and be flexible enough for practical implementation in PBD engineering.

To address this knowledge gap, we present a novel fire curve, specifically designed for WUI applications, called the "wildfire curve." This curve is derived from a statistically significant dataset. We collected over 20,000 temperature measurements using Unmanned Aerial Vehicles (UAVs) during a controlled 150 x 200 m² gorse shrub burn. The data was further verified with 25 in-situ temperature measurements and linked to the local wildfire behaviour using corresponding visual video footage and Light Detection and Ranging (LiDAR) data of the vegetation canopy.

2. MATERIAL AND METHODS

2.1. Site description and burning conditions

This section summarizes the experimental setup used to develop the wildfire curve presented in this work. The data originates from a prescribed shrubland fire conducted at Rakaia Gorge, Canterbury, New Zealand. Detailed descriptions of the site, setup, and fire campaign can be found in (Valencia, Melnik, Kelly, et al., 2023; Valencia, Melnik, Sanders, et al., 2023).

The fire experiment involved a 3-hectare flat plot aligned with the prevailing wind direction (Figure 1). The overstory canopy was dominated by gorse (Ulex europaeus L.) with some matagouri (Discaria toumatou Raoul) present. The understory consisted of various grasses, roses (Rosa sp.), California thistle (Cirsium arvense (L.) Scop), and Russell lupin (Lupinus polyphyllus Lindl). Vegetation distribution and fuel morphology were not uniform across the plot. Some areas had tall, dense vegetation (up to 2.5 meters), while others had short clumps of gorse interspersed with grass patches (down to 0.2 meters). As reported in Valencia et al. (Valencia, Melnik, Kelly, et al., 2023), this variation in fuel conditions resulted in highly variable fire behaviour, with different fire intensities and flaming durations in different areas of the plot.

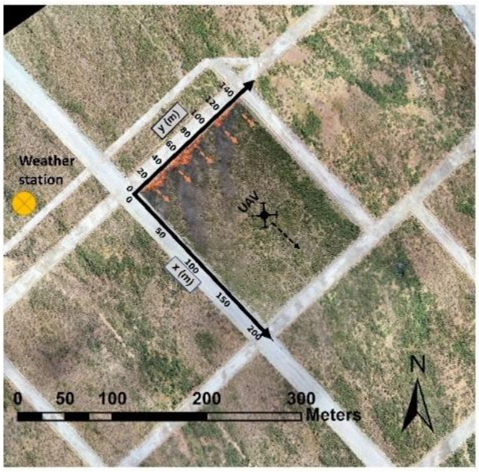

Figure 1. Top view of the experimental site.

The experimental plot was ignited on March 9th, 2020 at 12:17pm NZST. The average temperature, relative humidity and wind speed measured using a nearby weather station were respectively 23ºC, 33% and 9.8 m/s. Detailed information about experimental weather conditions, fire behaviour, consumption rate, destructive sampling and fuel load estimations are provided in (Valencia, Melnik, Kelly, et al., 2023).

2.2. Overhead infrared fire imagery and temperature measurements

To capture the spatial and temporal temperature changes across the plot during the fire, we employed a combination of aerial and in-situ measurements. A long-wave infrared camera (FLIR) with a spectral band of 8 μm–14 μm, mounted on a DJI Matrice 210 drone, captured brightness temperature. This camera was calibrated for high temperatures to prevent saturation and recorded data at 30 frames per second with a ground resolution of 3.6 cm/pixel. Additionally, nadir visual (RGB) videos were acquired at 12 MP resolution for situational awareness.

On the ground, K-type thermocouples were spaced uniformly across the plot, each cantered in a 25 m x 25 m area. These thermocouples recorded temperature data at a frequency of 1 Hz. Both the UAV and in-situ measurements were linked to fuel load (kg/m²), fireline intensity (kW/m), and residence time (s) to establish the applicability range of the wildfire curve and ensure high-quality input data. The methodology for mapping vegetation properties and wildfire behaviour is detailed in (Valencia, Melnik, Kelly, et al., 2023).

3. RESULTS AND DISCUSSIONS

3.1. Brightness Temperature Measurements

A sample (1 in 10,000) of brightness temperature measurements obtained from the overhead infrared footage (black lines) and their average (blue line) is shown in Figure 2. Each black line represents the brightness temperature recorded over time for a single pixel (0.36 x 0.36 meters), not the actual flame or gas temperature. Only measurements exceeding fireline intensities of 1000 kW/m² were included to minimize errors related to footage stabilization and flame visualization.

To ensure consistency, all measurements were adjusted to a reference system using a 100°C brightness temperature threshold, where a significant temperature rise was observed. The top horizontal axis (distance) represents a characteristic length calculated by multiplying the average rate of spread by the elapsed time. The ignition point (marked by the appearance of flaming combustion) was determined by carefully aligning the RGB and IR videos. This distinction separates preheating (negative time and distance) from flaming and smouldering combustion (positive time and distance).

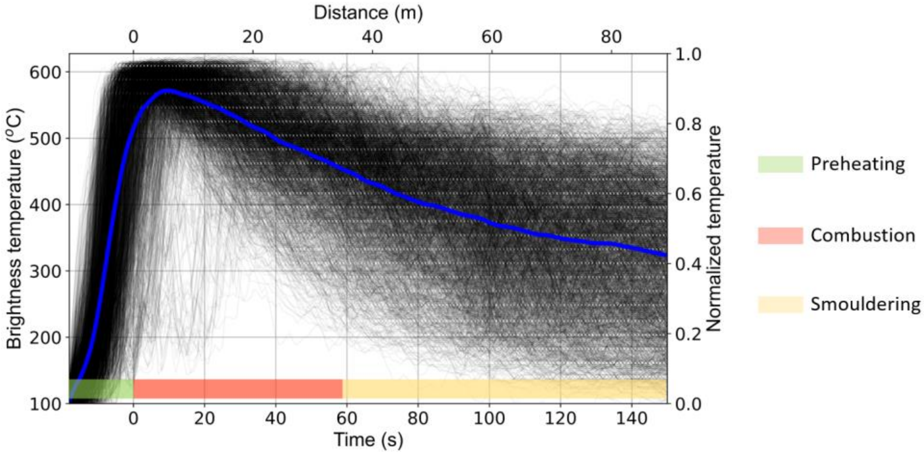

Figure 2. Brightness temperature measurements obtained from the overhead infrared (IR) footage (black lines) and their average (blue line) throughout the fire duration. A sample of 2000 out of 20,000 curves presented.

Our analysis of the fire stages revealed distinct characteristics. The preheating zone (green), lasting about 20 seconds before flaming combustion, exhibits a rapid rise in temperature due to a combination of factors: heating unburnt fuel, intermittent flame contact, and hot smoke. This zone extends roughly 10 meters ahead of the fire front. The flaming combustion zone (red), lasting about a minute on average, was found to reach the peak intensity around 10 seconds after ignition. The characteristic length of the combustion zone, which represents the average length of the flaming zone, was approximately 35 m, and the peak was located about 5 m inside the flaming zone from the fire front. This is followed by a decrease in temperature as the fire consumes fuel and transitions to a smouldering stage (yellow), which observations suggest can last for more than 2 minutes. The reduction of brightness temperature may be linked to a gradual decline of burning rate and volatile releasing, consequence of the fast consumption of small particles and charring layer production. This was perceptible during the experiment as a clear reduction of the length and coverage of the flames. The smouldering stage (yellow) was found to last more than 2 mins, and even 5 to 10 times more from visual inspection during the experiments.

3.2. Wildfire Curve

Brightness temperature represents the radiative energy emitted during wildfire events, which is function of the temperature of the gas and vegetation as well as of the fire's power output. The dimensionless form of this data (normalized temperature vs. time as shown in Figure 2), which we refer to as the "wildfire curve," can serve as a baseline for understanding how wildfire hazard metrics evolve over time. These metrics include heat release rate, mass loss rate, gas temperature, and emitted heat flux under various burning conditions. To achieve this, we developed the following empirical correlations (Eq. 1 and Eq. 2):

$$f_n(t) = ae^{-(\frac{t+b}{c}+k(t))} \tag{1}$$

$$k(t) = e^{-\frac{t+d}{g}} \tag{2}$$

Where *fn* is the wildfire curve (from 0 to 1), *t* the time and *a, b, c, d* and *g* are empirical coefficient derived from experimental curve fitting. While the exponential function *k*(t) provided the highest accuracy, other simpler functions yielded acceptable results as well. The model's effectiveness was evaluated by fitting it to over 20,000 experimentally acquired normalized brightness temperature curves (including the 2,000 black curves and their average blue curve in Figure 2) and in-situ temperature data measured by thermocouples. Some examples are provided in Figure 3.

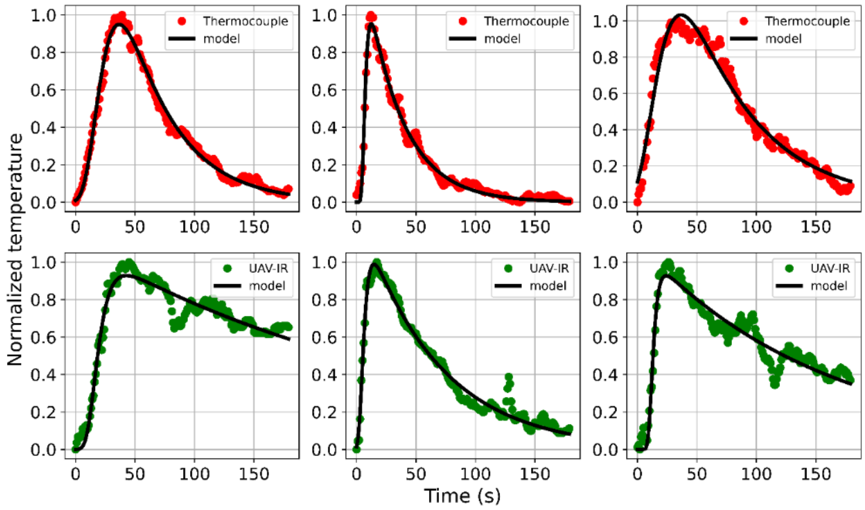

Figure 3. Comparison of normalized temperature from model (Eq. 1 and 2) to in-situ temperature from thermocouple (in-situ) and brightness temperature from overhead IR measurements.

A single set of coefficient *a* (range 10 to 250 approx.), *b* (range 400 to 2000 s approx.), *c* (range 100 to 500 s approx.), *d* (range between 2 to 30 s approx.) and g (range between 1 and 10s approx.) were obtained for each experimental curve via least-square analysis. The calculated mean absolute difference was very low (8%), suggesting that the proposed model can to be used as a wildfire curve.

Assuming that the profile of the wildfire curve (represented by Eq.1 and Eq.2) is similar to the temporal evolution of the power of the wildfire allows for estimation of the heat release rate over time, which is a key variable in fire hazard calculations. For a known fuel load m'' (kg/m^2) and effective heat of combustion Δh (J/kg), a set of coefficients (*a, b, d, c, d* and *g*) satisfying Eq. 3 can be found:

$$m''\Delta h = \int_{t_o}^{t_e} f_n(t)\,dt = \int_{t_0}^{t_e} \dot{Q}''(t)\,dt \tag{3}$$

Where t_0 and t_e are correspondingly the ignition and extinction time and $\dot{Q}''$ is the heat release rate per unit of surface are (W/m^2) which will be represented by the wildfire function f_n. This approach offers a new method for estimating other metrics such as smoke plume composition, temperature and speed, radiative heat flux, flame height which have been previously correlated to heat release rate. This approach provides a more reliable basis for developing design fires and scenarios compared to existing methods, such as proposed in (Cantor et al., 2022; Penney & Richardson, 2019), which may overestimate wildfire impacts. This improved accuracy is crucial for verifying performance-based design in both urban planning contexts and fire safety engineering.

4. LIMITATIONS

For brevity, we focus on a key limitation of the proposed methodology. This limitation concerns the complex relationship between the signal captured in the IR spectrum and the heat release rate. This signal arises from a combination of thermal radiation from burning vegetation surfaces and soot particles, as well as spontaneous emissions from hot combustion species. Currently, this relationship is not fully understood. Ongoing laboratory experiments employing calorimetry, gas temperature, and IR cameras aim to elucidate this relationship and validate the linkage between brightness temperature, gas temperature, and heat release rate.

5. CONCLUSIONS

This study effectively addresses the limited applicability of traditional fire curves in wildland-urban interface (WUI) design. The research introduces a novel "wildfire curve" specifically developed for WUI environments. This curve is derived from a rich dataset collected during a controlled burn, including over 20,000 brightness temperature measurements captured by UAVs, complemented by in-situ temperature probes and LiDAR data. The paper further proposes a methodology to estimate heat release rate based on the wildfire curve. This combined approach offers a more comprehensive and data-driven foundation for fire engineering design and risk assessments in WUI communities.

By enabling engineers to incorporate the unique wildfire behaviour in WUI setting, this approach has the potential to improve building resilience, enhance safety for residents, and ultimately reduce potential damage from wildfires in these vulnerable areas.

6. ACKNOWLEDGMENTS

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