ADVANCES IN FOREST FIRE RESEARCH

2022

Edited by
DOMINGOS XAVIER VIEGAS
LUÍS MÁRIO RIBEIRO

Intermittent fireline behavior over porous vegetative media in different crossflow conditions

Abhinandan Singh*; Reza M. Ziazi; Albert Simeoni

Department of Fire Protection Engineering, Worcester Polytechnic Institute, Worcester, MA, USA, {asingh4, rziazi, asimeoni}@wpi.edu

**Corresponding author*

Keywords

Fire spread, Flame pulsations, Flame residence, Ignition, Flame leaping

Abstract

Detailed physical understanding of fire spread is important in the face of the increasing frequency of wildland fires around the globe. Historically, fire spread across porous vegetative media has been considered a continuous phenomenon. Most studies neglect the influence of flame pulsations on the ignition of fuel particles ahead of the fire front, hence approximating the fire spread to a steady and continuous process. This research explores the dynamic nature of fire propagation by experimentally examining the instantaneous flame pulsations and their impact on the ignition of virgin fuel particles. Fire spread experiments were conducted over a longleaf pine needle (Pinus Palustris) testbed under varying crossflow conditions. In addition to introducing a flame tilt, the presence of crossflow strongly enhances the pulsating nature of a free-burning fire. The flame region of influence ahead of the fireline was augmented by the flame tilt and flame pulsations thereby leading to point ignitions at a distance. If sustained, these point or flash ignitions merge with the fireline, leading to flame spread in the form of leaps. Fire behavior was evaluated by conducting detailed image analysis of videos acquired by placing various cameras around the testbed. Additionally, local temperature and flow velocity were measured by placing a series of thermocouple trees and bi-directional probes within the fuel bed. A curved flame profile was observed under wind-aided conditions, and the curvature was seen to increase with the increasing velocity. Alternatively, a flat temperature profile was observed for no wind conditions. Under forced flow conditions, the bi-directional probes within the testbed measured the flow blocking effect (drag forces) and the presence of flame greatly enhanced the local flow velocity.

1. Introduction

Rapid changes in the global climate (Ellis et al. 2021) and years of inefficient land management techniques (Hann and Bunnell 2001) are the major reasons behind the increased frequency of high-intensity wildland fires. The future global average temperature is expected to follow an increasing trend (Arnell et al. 2009), which will further reduce the fuel moisture content (Keeley and Syphard 2016) and thereby increase the frequency and intensity of large wildland fires. Proximity of the human population to the forested regions and increase in the wildland urban interface (WUI) (Radeloff et al. 2018) adds urgency to this problem. Reliable fire spread models require a thorough physical understanding of the fire spread phenomenon under varying atmospheric conditions. A significant portion of wildland fire literature focuses on understanding flame spread across vegetative fuel, which has further been utilized to build and validate various fire spread models.

The pulsating nature of free-burning fires under the influence of crossflow has been studied using burners (Tang et al. 2019), pool fires (Lin et al. 2021), cribs (McAllister and Finney 2016), engineered cardboard (Finney et al. 2015), and most importantly vegetative fuel (Simpson et al. 2014). Non-spreading flames are helpful in evaluating the fire behavior under changing external conditions but with limited conclusions that may or may not be applicable to the flame spread problem. This work draws an understanding from the pulsating nature of non-spreading flames and furthers it to evaluate the influence of flame pulsations on particle ignition and flame spread behavior. Flame spread is mostly considered as a continuous movement of fire through spontaneous ignitions ahead of the fire front. However, the non-continuous nature of flame spread has been recently studied (Viegas et al. 2021) through various experimental studies. This research focuses on the non-continuous and dynamic motion of the fire front through a pine needle testbed. The multi-scale interaction between wind, fire, and topography makes the fire spread a dynamic phenomenon, that can influence the development of a fire. Hence, the quantification of this dynamic fire behavior is important for accurate fire prediction.

Flame pulsations during flame spread was first explored in the context of the *trench effect* (Atkinson et al. 1995, Smith 1992, Drysdale et al. 1992) where pressure pulsations were measured by placing probes along the flame spread direction. The controlling physical mechanism generating these pressure variations was observed to change with the trench orientation. Frequency and magnitude of these pulsations were inversely related (Atkinson et al. 1995). Recent work by Finney et al. (2015) examined the flame intermittencies and described the importance of convective heating for fire propagation. Delayed ignition due to intermittent particle heating was also analyzed and continuous flame presence was shown to be necessary for particle ignition and hence fire spread. In the current research, flame pulsations and their impact on particle ignition and fire spread are explored using image analysis and video observations. Delayed fire movement is also examined using temperature measurements while local flow measurements show flow blocking and air entrainment.

2. Experimental details

Fire spread experiments were conducted under various crossflow conditions using a well-characterized wind tunnel, shown as a schematic in Fig. 1(a). These experiments used a *Pinus Palustris* testbed (1650mm by 600mm) placed inside the tunnel with an ignitor embedded in the sand at the leading edge. Sand was used as the pine needles' base to emulate a natural setting. Baked insulation board was used to make the ignitor wick of width 600mm and length 15mm which was soaked with ~20ml of liquid methanol. The ignitor flame was initiated using a heated Nichrome wire placed across the width of the wick top surface. Since methanol generates a clean fast-burning flame, fire spread independent of the ignitor was observed within the first 400mm of the testbed. Fire spread behavior was qualitatively and quantitatively analyzed for five different flow conditions, namely 0, 0.23, 0.28, 0.42, and 0.75m/s. The fuel loading was kept constant at $0.5\mathrm{kg/m^2}$ and the fuel moisture content (FMC) varied between 5 and 7% on a dry basis.

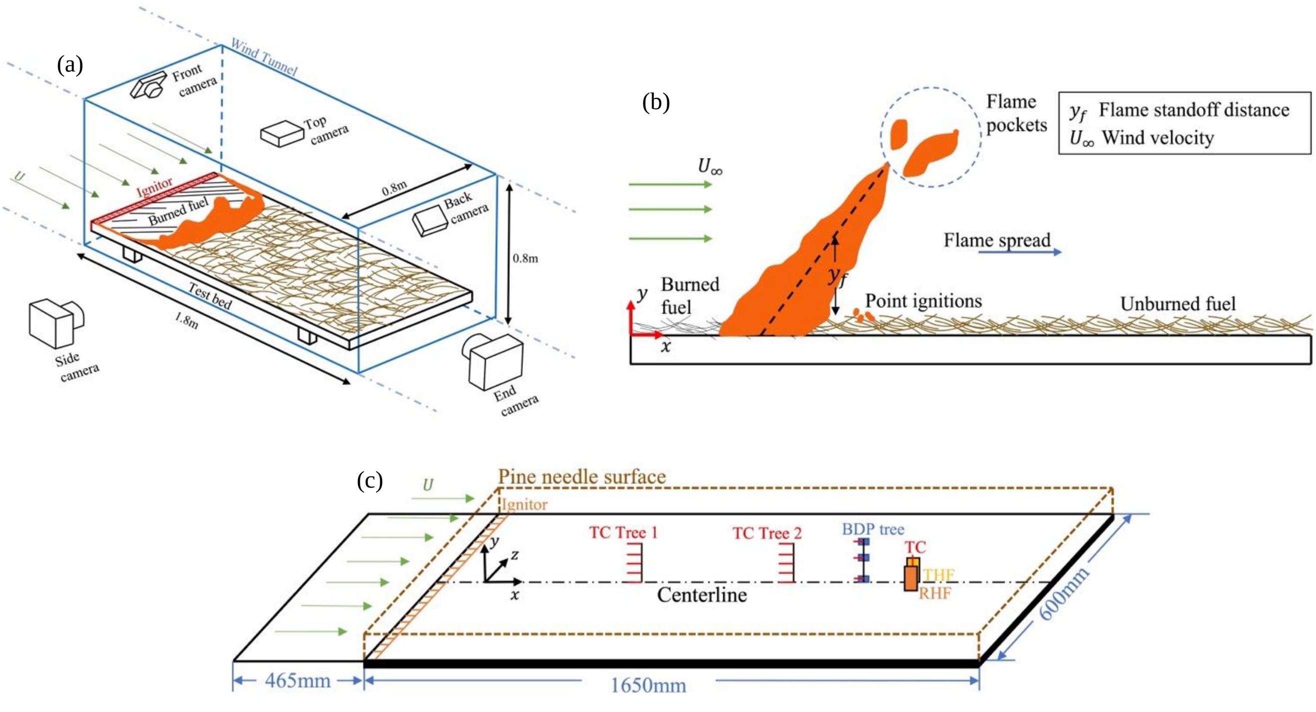

Figure 1 - (a) Schematic of the testbed placed inside the wind tunnel along with the cameras. (b) Fire spread behavior through a pine needle testbed (c) Testbed with the sensor setup.

A schematic of the sensor layout within the testbed is shown in Fig. 1(c). The testbed consisted of two thermocouple trees composed of five K-type thermocouples of 150µm wire-diameter each placed at x = 540mm and x = 1040mm from the leading edge. Five thermocouples were placed in each tree at five different heights with equal increments of 23mm starting from the bottom of the bed (z = 0, 23.3, 46.6, 70, and 93.2mm). Three 10mm diameter bi-directional probes (BDPs) were also placed in a tree-like arrangement (z = 0, 70 and

93.2mm) at x = 1250mm from the leading edge. A K-type thermocouple was attached to each BDP for density correction and flame location. Heat flux measurements were conducted by placing a radiometer and total heat flux gauge at x = 1400mm along with a K-type thermocouple to assess the flame location. Temperature and heat flux measurements were carried out at a sampling rate of 75Hz while pressure was measured at a frequency of 220Hz. Five cameras were placed above and around the testbed to observe the fire behavior as the flame front moved along the testbed.

A detailed image analysis algorithm was developed using the previously established technique (Singh and Singh 2021) of generating flame probability contour profile for non-spreading flames by assuming negligible fire front movement within 0.5s. Side-view cameras acquired the videos at 120 frames per second and every 60 frames (0.5s) were binarized and averaged to build an instantaneous contour profile, which was used to extract the mean and intermittent flames. Additionally, the videos were qualitatively analyzed to observe the flame pulsations and their influence on particle ignition and fire spread.

3. Results and discussions

A detailed qualitative analysis is presented in this section by conducting visual observations using various videos acquired from cameras placed around the testbed. This qualitative analysis is verified by comparison with the temperature and velocity measurements. To understand fuel particle ignition and fire front movements, flame pulsations in the form of mean and intermittent flame are evaluated. The increased region of influence of the fire front is seen to cause point ignitions leading to flame leaping, which is observed from the side, top and back cameras.

3.1. Flame pulsations – Mean and intermittent flame

Buoyancy-induced instabilities and air entrainment lead to flame pulsations generating a mean and intermittent flame. This intermittent flame appears in the form of flame pockets separating from the mean fire front along the direction of flame orientation. A robust image analysis technique was used to evaluate the mean and intermittent flame regions (Singh and Singh 2021, Sun et al. 2021) using the videos acquired from the side-view camera. It is observed from Fig. 2 that for the same wind velocity, the flame region of influence increased due to the presence of the intermittent flame and the area of intermittent flame increased with increasing crossflow momentum. Furthermore, the flame tilt generated under the influence of crossflow decreased the *flame standoff distance* (see Fig. 1(b)), leading to an increased preheating of the unburnt fuel particles ahead of the fire front.

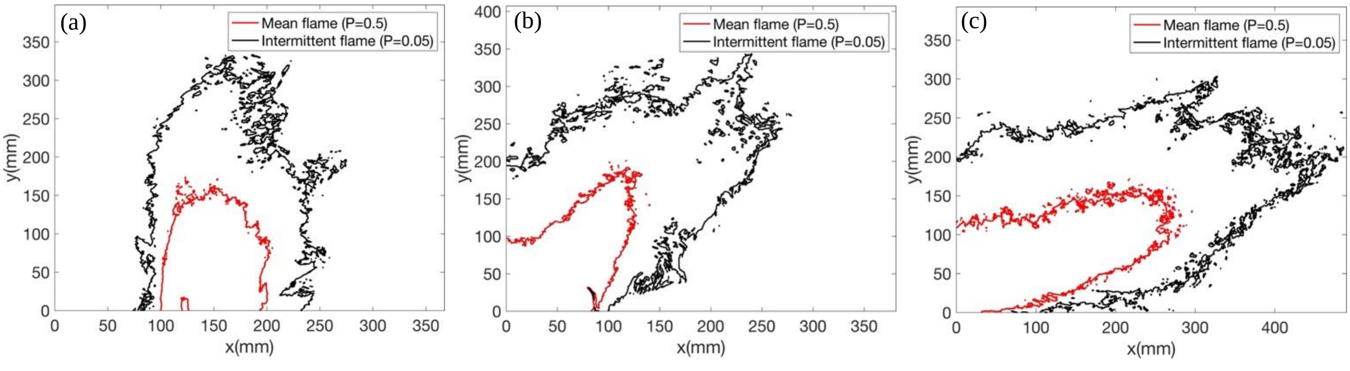

Figure 2 – Mean and intermittent flame contour profiles evaluated using 60 frames (0.5s) for (a) 0m/s, (b) 0.23m/s, and (c) 0.75m/s flow.

3.2. Ignition and fire line movement

Fire front acts as an obstacle for the flow, which intermittently breaks through this barrier, pushing the hot gases towards the unburnt fuel (Finney et al. 2015). This increases the flame region of influence and causes intermittent point ignitions ahead of the flame. This phenomenon is presented in Fig. 3 using the back view for 0.42m/s case with time t = 0s taken as the first frame. Point ignitions, represented by the dotted blue line, have dynamic nature, and depend upon the instantaneous heating conditions. Under low heating conditions, these point ignitions are seen to extinguish and then re-ignite, as observed between t = 0.099s and t = 0.132s. The fire front stagnates at a given *x*-location until the point ignitions merge with the fire front, leading to *flame leaping* over the top surface (at t = 0.198s). This behavior is seen to continue throughout the testbed and under varying wind velocities.

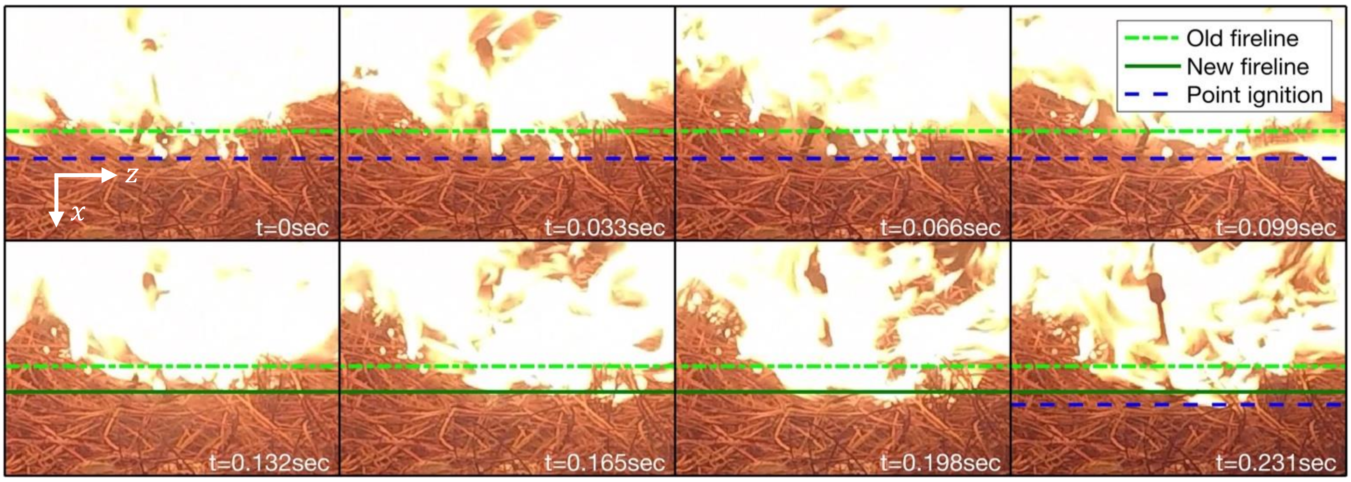

Figure 3 – Intermittent point ignitions and flame spread in the form of leaps for a wind velocity of 0.42m/s. The frames are extracted from the video captured using the back camera.

3.3. Local temperature and flow variations

Two thermocouple trees were placed along the testbed centerline to evaluate the flame behavior during fire front stagnation. Flame presence at a location was acquired using a threshold temperature of 300°C (Mueller et al. 2018). Figure 4 contains the flame profile measured by both the thermocouple trees for wind velocity of 0m/s, 0.28m/s and 0.75m/s. Fire spread under no-flow condition shows a flat flame profile, while this flatness was lost with the introduction of cross wind. For wind-aided fire spread, the flame skimmed over the top surface of the fuel bed, while a delayed movement was observed through the bed, leading to a curved flame profile throughout the bed.

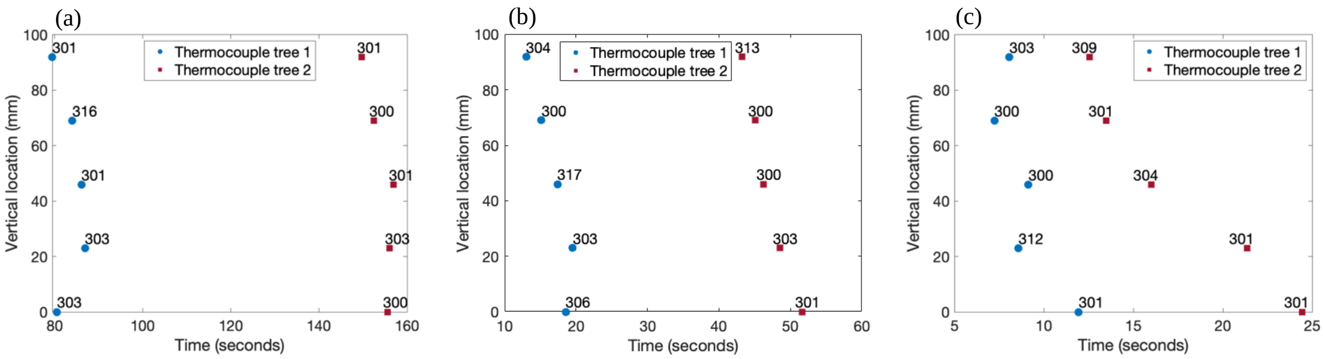

Figure 4 – Flame profile measured using two thermocouple trees consisting of five thermocouples at various vertical locations for wind velocities of (a) 0m/s, (b) 0.28m/s, and (c) 0.75m/s.

The flow velocity measured at the fuel bed surface (=70mm) using a bi-directional probe is presented in Fig. 5 for crossflows of 0m/s, 0.28m/s and 0.75m/s. Temperature measurements at the same location are also presented in the same graph. Near-zero velocity fluctuations were initially observed for all the crossflow wind speeds, representing the flow blockage effect by the porous vegetation. This flow blockage delays the fire movement through the fuel bed, thereby causing the flame to skim over the top surface. For no-flow and low-wind conditions, a significant reduction in the velocity, leading to negative or reverse flow can be seen. This reverse flow represents cold-air entrainment that leads to convective cooling and possible extinction of the point-ignitions ahead of the fire front. No reverse flow is observed for a wind velocity of 0.75m/s because the forced momentum dominates over the induced air entrainment near the fire front.

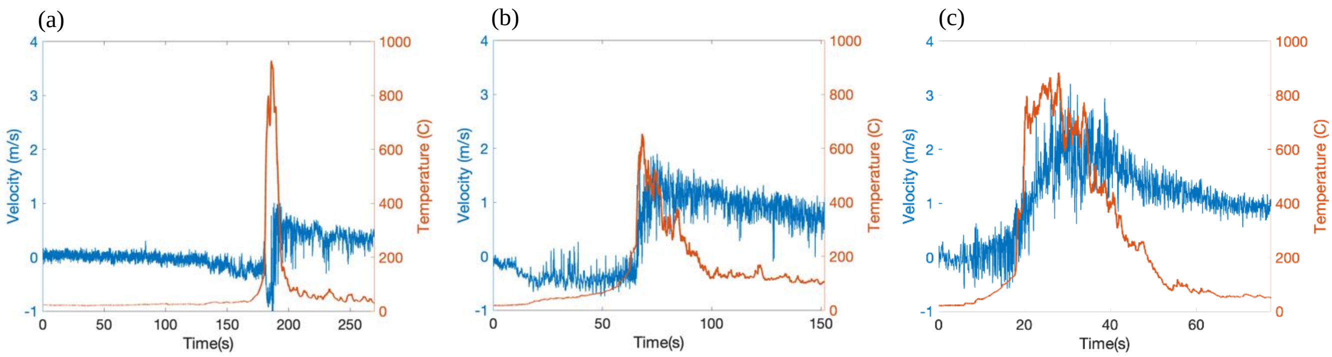

Figure 5 – Local flow velocity and corresponding temperature measured along the top surface of the testbed for wind velocities of (a) 0m/s, (b) 0.28m/s, and (c) 0.75m/s.

4. Conclusions

This work experimentally investigated the dynamic nature of flame spread over a pine needle testbed under varying crossflow conditions. Buoyancy-induced flame pulsations and their interaction with wind was seen to increase the flame region of influence. The flame standoff distance was also seen to decrease with the crossflow momentum, thereby enhancing fuel preheating. The increased flame influence leads to point ignitions in the unburnt fuel ahead of the fire front. These point ignitions can grow under suitable conditions and eventually merge with the fire front leading to flame spread in the form of leaps. Fire front is observed to halt before leaping to a new downstream location. During this flame front pause, it was seen that the fuel bed top surface experiences the flame while flow blockage within the fuel bed delays the fire spread through the bed. Furthermore, the cold air entrainment ahead of the fire front causes convective cooling of point ignitions, leading to extinction and re-ignition. On re-ignition, these point sources grow and merge with the fire front, leading to flame spread. Quantification of the observed point ignitions and leaping phenomenon will be conducted in the future work alongside building a theoretical understanding for intermittent fireline movement.

5. Acknowledgements

This work was funded by the U.S. Department of Defense Strategic Environmental Research and Development Program, project RC20-1304, and the U.S. Environmental Protection Agency, grant number 84006801.

6. References

Arnell, N.W., Lowe, J.A., Challinor, A.J. and Osborn, T.J., 2019. Global and regional impacts of climate change at different levels of global temperature increase. *Climatic Change*, *155*(3), pp.377-391. https://doi.org/10.1007/s10584-019-02464-z

Atkinson, G.T., Drysdale, D.D. and Wu, Y., 1995. Fire driven flow in an inclined trench. *Fire safety journal*, *25*(2), pp.141-158. https://doi.org/10.1016/0379-7112(95)00039-9

Drysdale, D.D., Macmillan, A.J.R. and Shilitto, D., 1992. The King's Cross fire: Experimental verification of the 'Trench effect'. *Fire Safety Journal*, *18*(1), pp.75-82. https://doi.org/10.1016/0379-7112(92)90048-H

Ellis, T.M., Bowman, D.M., Jain, P., Flannigan, M.D. and Williamson, G.J., 2021. Global increase in wildfire risk due to climate-driven declines in fuel moisture. *Global change biology*. https://doi.org/10.1111/gcb.16006

Finney, M.A., Cohen, J.D., Forthofer, J.M., McAllister, S.S., Gollner, M.J., Gorham, D.J., Saito, K., Akafuah, N.K., Adam, B.A. and English, J.D., 2015. Role of buoyant flame dynamics in wildfire spread. *Proceedings of the National Academy of Sciences*, 112(32), pp.9833-9838. https://doi.org/10.1073/pnas.1504498112

Hann, W.J. and Bunnell, D.L., 2001. Fire and land management planning and implementation across multiple scales. *International Journal of Wildland Fire*, 10(4), pp.389-403. https://doi.org/10.1071/WF01037

Keeley, J.E. and Syphard, A.D., 2016. Climate change and future fire regimes: examples from California. *Geosciences*, 6(3), p.37. https://doi.org/10.3390/geosciences6030037

Lin, Y., Hu, L., Zhang, X. and Chen, Y., 2021. Experimental study of pool fire behaviors with nearby inclined surface under cross flow. *Process Safety and Environmental Protection*, *148*, pp.93-103. https://doi.org/10.1016/j.psep.2020.10.011

McAllister, S. and Finney, M., 2016. Burning rates of wood cribs with implications for wildland fires. *Fire technology*, *52*(6), pp.1755-1777. https://doi.org/10.1007/s10694-015-0543-5

Mueller, E.V., Skowronski, N., Thomas, J.C., Clark, K., Gallagher, M.R., Hadden, R., Mell, W. and Simeoni, A., 2018. Local measurements of wildland fire dynamics in a field-scale experiment. *Combustion and Flame*, *194*, pp.452-463. https://doi.org/10.1016/j.combustflame.2018.05.028

Radeloff VC, Helmers DP, Kramer HA, Mockrin MH, Alexandre PM, Bar-Massada A, Butsic V, Hawbaker TJ, Martinuzzi S, Syphard AD, Stewart SI. Rapid growth of the US wildland-urban interface raises wildfire risk. Proceedings of the National Academy of Sciences. 2018 Mar 27;115(13):3314-9. https://doi.org/10.1073/pnas.1718850115

Simpson, C.C., Sharples, J.J. and Evans, J.P., 2014. Resolving vorticity-driven lateral fire spread using the WRF-Fire coupled atmosphere–fire numerical model. *Natural Hazards and Earth System Sciences*, *14*(9), pp.2359-2371. https://doi.org/10.5194/nhess-14-2359-2014

Singh, A., and Singh, A.V., 2021. Burning behavior of mixed-convection wind-driven flames under varying freestream conditions. *Fire Safety Journal*, *122*, p.103320. https://doi.org/10.1016/j.firesaf.2021.103320

Smith, D.A., 1992. Measurements of flame length and flame angle in an inclined trench. *Fire safety journal*, *18*(3), pp.231-244. https://doi.org/10.1016/0379-7112(92)90017-7

Sun, X., Hu, L., Zhang, X., Ren, F., Yang, Y. and Fang, X., 2021. Experimental study on flame pulsation behavior of external venting facade fire ejected from opening of a compartment. *Proceedings of the Combustion Institute*, *38*(3), pp.4485-4493. https://doi.org/10.1016/j.proci.2020.06.181

Tang, W., Finney, M., McAllister, S. and Gollner, M., 2019. An experimental study of intermittent heating frequencies from wind-driven flames. *Frontiers in Mechanical Engineering*, *5*, p.34. https://doi.org/10.3389/fmech.2019.00034

Viegas, D.X.F.C., Raposo, J.R.N., Ribeiro, C.F.M., Reis, L.C.D., Abouali, A. and Viegas, C.X.P., 2021. On the non-monotonic behaviour of fire spread. *International journal of wildland fire*, *30*(9), pp.702-719. https://doi.org/10.1071/WF21016