



Forced convection fire spread along wooden dowel array

Giovanni Di Cristina^a, Shijin Kozhumal^b, Albert Simeoni^c, Nicholas Skowronski^d,
Ali Rangwala^c, Seong-kyun Im^{a,e,*}

^a Department of Aerospace and Mechanical Engineering, University of Notre Dame, USA

^b Department of Fire Protection and Paramedicine Sciences, Eastern Kentucky University, Richmond, KY, USA

^c Department of Fire Protection Engineering, Worcester Polytechnic Institute, USA

^d USDA Forest Service, Northern Research Station, Morgantown, WV, USA

^e Department of Mechanical Engineering, Korea University, Seoul, South Korea

ARTICLE INFO

Keywords:

Flame spread
Wood combustion
Discrete fuels
Fluid dynamics

ABSTRACT

The effects of freestream flow on fire spread behaviors of a discrete wooden fuel array were studied. The spacing between fuel elements was varied, and the flame spread behavior under 1, 2, and 3 m/s forced flow velocities was investigated. The fastest spread rate was not observed for the smallest spacing. Furthermore, increasing spacing did not necessarily lead to a slower spread, as seen with the flame spread along the 0.75 cm spaced array which was as fast or faster than the 0.5 cm spacing condition. At a spacing of 1 cm, fragmented flames were observed at wind speeds of 3 m/s that coincided with a slower spread rate than the 2 m/s wind conditions. The anomalies were explained using flame visualization and pitot probe measurements to determine the effects of flow speed at different spacing conditions. It seems that a coupling between the combustion and fluid dynamics of flow around the dowel cylinders under certain conditions strongly affects the fire spread behaviors.

1. Introduction

A variety of flame spread scenarios, such as wildland fires, urban structure fires, and interior fires, can be thought of as complex systems of discrete fuel flame spread. Researchers have often used arrays or fuel beds of wooden sticks, paper strips, cardboard or other simple fuels to simplify the study of these complex fire scenarios [1–11]. The studies found that the fine fuels are the first to ignite and have an important contribution to the initial fire spread, and the spread rate depends on fuel setting and flow conditions. For example, small scale fuels on the ground (shrubs and grass) or on trees (twigs and branches) could be burned easier than trees in the initial stage of wildfire. Thus, research on fire spread of small scale fuels has been extensively conducted.

Early work by Fons [1] and Emmons [2,12] took steps to model the consecutive ignition of fuel elements in arrays and fuel beds to represent nonhomogeneous forest fuel beds. Vogel and Williams [13] examined the spread along short matchsticks (with the head removed) mounted on a plate at different spacing conditions and found that the spread can be approximated using a linear geometric model and 1-dimensional approximations to represent heat transfer. Further studies investigated similar fuels under slow constant wind [14]. Some research, for

example, Emmons [15] and Kosdon et al. [16], explored the dynamics of the downward propagation along single wooden dowels and the effect of different environmental conditions on the spread rate. More recently, Jiang et al. [17] examined the vertical spread of buoyancy-driven convection along multiple configurations of 2D arrays, using a convective heat transfer model to predict upward flame spread. Past studies have featured differing degrees of convective flow ranging from buoyancy-driven natural convection to flows up to 1 m/s.

Experiments with no imposed flow field [3,9] show a constant flame spread that is successfully modeled with 1-D thermal physics or geometric arguments. These models have also been shown to extend to sloped arrays, imposing a flame angle, which has been argued to also represent the tilting effect of wind on the flame plume [10]. Vertically arranged array flame spread provides a slight flow (assumed to be the induced buoyancy velocity) as the convective flow parameter, however, because there is no overall flow field but rather slowly increasing hot gasses from the combustion, the flow effects are minimal and each element is treated as unaffected by upstream flow disturbances [6,8,17]. Furthermore, the approximated maximum speed of the gasses is around 1.5 m/s. Lastly, horizontally arranged forced flow studies have shown that convection and turbulent diffusion are primary heat transfer

* Corresponding author. Department of Mechanical Engineering, Korea University, Seoul, South Korea.

E-mail address: sim3@korea.ac.kr (S.-k. Im).

<https://doi.org/10.1016/j.firesaf.2020.103090>

Received 3 January 2020; Accepted 28 April 2020

Available online 6 May 2020

0379-7112/© 2020 Elsevier Ltd. All rights reserved.

mechanisms in these systems [18], but few past studies have examined flows greater than 1 m/s, where the buoyancy effects are still comparable to momentum from the imposed flow field [14].

The developed models to predict fire spread in these past studies do not consider any coupling between the wind and flame, but rather the wind serves to only increase flame contact and heat transfer as a laminar flame. In order to bolster the accuracy of these models, the interactions between flame and flow need to be investigated. The presented research bases its premise on the past works mentioned above, with a few key distinctions. In contrast to past studies, wooden dowels are suspended to avoid boundary effects from a flat surface and use round instead of square cross-sections. The array of wooden dowels is then subject to flow speed ranges higher than previously studied. It has been reported that at relatively high flow speeds (around 3 m/s) fire spread around the 2.5 mm diameter scale becomes unsteady [18,19]. Also, studies of cylinders in non-reacting cross-flow have found that the inter-cylinder region turbulence and mixing are highly dependent on the vortex shedding behavior of the upstream cylinder [20–25]. The current study aims to better characterize the effect of wind on fire spread in unsteady spread regimes.

2. Experimental design and methodology

2.1. Experimental design

Fig. 1 shows the experimental setup and relevant parameters. For this study, 3.2 mm diameter pine wooden dowels cut to 26 cm in length were used. The thickness chosen is similar to prior studies [3,4,6,8] examining fire spread in discrete elements, which are also representative of the small-scale fuels that drive fire spread. Prior to testing, the dowels were dried until they reached 5% moisture content. The dowels were placed in a linear array suspended on both ends approximately 12 cm above the wind tunnel floor where outside the boundary layer of the flow. Thus, interference effects from the wind tunnel wall boundaries could be eliminated. Furthermore, the test conditions could more closely represent suspended twigs and small branches on trees. The suspended dowels were placed 3 m downstream of the test section inlet of a wind tunnel (Fig. 1). The tunnel is composed of a 5 m long diverging section and two fans capable of providing uniform flow up to 8 m/s and a turbulence intensity up to 20% at the test section inlet. The test section, with a flow cross-sectional area of 1.5 m × 2.26 m, has a total length of 6 m and features large transparent windows capable of enduring direct flame contact with temperatures up to 1200 K for an hour. The transparent windows allow optical access to the test section for flame visualization and optical measurements.

The first dowel in the array was wrapped with a jute rope coil soaked with 0.3 ml of Kerosene to provide a pilot ignition. The freestream flow was blocked during pilot ignition for 30 s to ensure that the kerosene was burned away and interference from transient flow features during tunnel fan start-up were eliminated. The flame propagation of the 10-element dowel array was studied for five spacings (0.5, 0.65, 0.75, 1, and 1.15 cm) at three freestream flow conditions (1, 2, and 3 m/s). Fire spread

was captured using a GoPro Hero5 camera at 60 frames/sec. A pitot probe was used to measure pressure fluctuations in the non-reacting flow behind the dowel array approximately 6 cm above the bottom attachment point. The probe was connected to an Omega PX-275 differential pressure transducer sampling at 1 kHz.

2.2. Ignition characterisation

Ignition of a dowel was experimentally determined by analyzing captured flame spread video and flame locations. The minimum flame jump time from one dowel to the next is about 0.5 s. The video captures at 60 frames/s. Thus, it allows approximately 30 images to calculate the flaming ignition of one dowel to the next in detail. The methodology used to process the images is shown in Fig. 2. Where the ignition determination procedure for a representative 1 cm spacing and 3 m/s freestream velocity is used. To determine when a dowel is ignited, the pixel intensity values were measured along a vertical column near the surface of the dowel of interest where it is expected to ignite. The pixel values are examined frame by frame until a jump is seen as compared to the previous frame and confirmed with the image. The frame corresponding to the spike in pixel values is marked as the time of ignition. The ignition determination procedure is repeated for all the dowels in the array and across five repeated experiments providing a maximum experimental uncertainty of ±0.5s. The uncertainty is based on the time difference between the image frames prior to and at ignition. In Fig. 2, subfigures (a), (b), and (c) correspond to dowel positions 3, 5, and 7 in the array. The first image of each subfigure is the time just before observed ignition of the center dowel. The middle image is at the time of ignition, and the last image is 1 s after ignition. Pixel intensity plots along the vertical dashed line are shown on the right of each image triplet for the corresponding time stamps. The results from the ignition determination provide time and location of ignition. Thus, ignition and flame propagation characteristics such as critical spacing for ignition and flame spread rate can be obtained.

3. Results and analysis

3.1. Critical spacing

For horizontal flame propagation along discrete fuels under no freestream velocity, the fire spread from element to element has been found to be constant [10,13,14,26,27], relying on the flame from one element to make contact with the next element to initiate ignition. The increasing spacing between elements only serves to slow down the fire spread due to the reduced flame contact with the next element. However, when a freestream velocity is applied, the most immediate effect is to tilt the flame causing much earlier impingement on the adjacent fuel elements, leading to faster forward flame propagation. In addition, spacings where flame propagation is not possible under natural conditions (zero free stream velocity) can now sustain flame spread as shown in Fig. 3 where regions that flame does and does not propagate with varying spacing and flow velocity are depicted. As spacing is increased, a

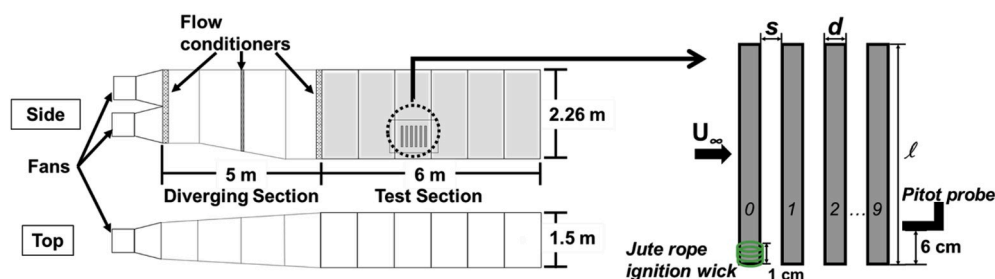


Fig. 1. Schematics of wind tunnel and experimental setup showing edge-to-edge spacing ($s = 0.5, 0.65, 0.75, 1, 1.15$ cm), dowel diameter ($d = 3.2$ mm), freestream flow ($U_\infty = 1, 2, 3$ m/s) and length ($l = 26$ cm). The dowel position numbering scheme utilizes 0 for the pilot dowel, then 1, 2, up to 9.

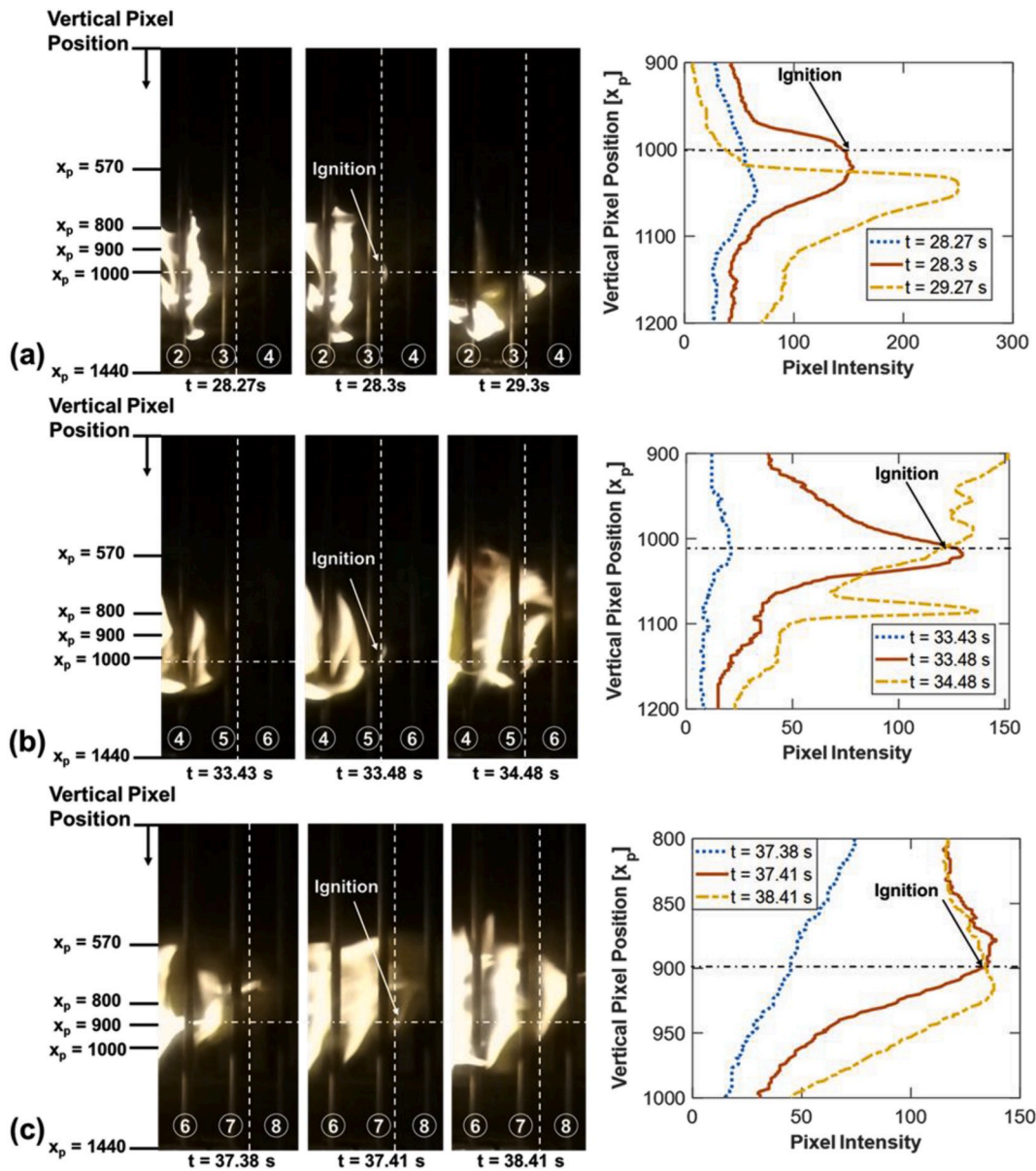


Fig. 2. The ignition determination procedure is shown for early (a) mid (b) and late (c) stages of fire spread along a 1 cm spaced array at 3 m/s flow speed. Pixel intensity plots for each time stamp along the vertical dashed line are shown on the right of each image set.

higher free stream velocity is needed to sustain continuous flame spread.

The spacing beyond which the adjacent element fails to ignite and thereby stopping forward propagation is defined as the critical spacing.

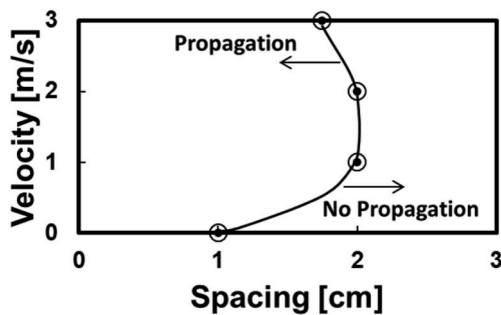


Fig. 3. Critical spacing for 3.2 mm dowel array. The line marks the marginal propagation threshold for which arrays at larger spacings do not see flame spread.

At the no flow conditions, the flame is purely buoyant, and the flame front extends to a limited distance. Thus, conduction and radiative heat transfer are the main heat transfer modes for pyrolysis and ignition of downstream dowels, and the critical spacing for the no flow conditions is less than those with a freestream flow. When a freestream velocity is applied, the flame tilts and contacts downstream dowels. In this manner, flame buoyancy is decreased by the effects of convective flow on the fire spread. Furthermore, because of the increased flame contact and flow advection, the rate of heat transfer increases as both convective and conductive effects from flame are increased in addition to the radiative heating. Consequently, the critical spacing increases in the presence of the cross-flow.

At low velocities, the convective flow and the flame's buoyancy have a comparable influence on the flame shape forming a steep angle. At an intermediate velocity, the convective flow plays a dominant role in the flame angle, forming a shallower angle, but overall the flame retains a similar shape as the 1 m/s case. Eventually, the flow speed becomes strong enough to flatten the top of the flame, and the flame takes on a different shape than the slower speeds. Based on the changes in the

flame shape and tilt angle, it can be assumed that the convective heat transfer could be significantly changed compared to a no flow scenario. Heat could be gained or lost to the freestream flow through convective heating or cooling, respectively. Additionally, the flame impingement area is increased due to a wind. Therefore, there could exist a competing effect between the flame and the flow. Lastly, the fluid dynamics induced by the interactions between the flow and the array elements subsequently affect combustion. Initially and up to 2 m/s, the addition of wind allows the flame to spread at higher spacings when compared to a no flow condition. However, increasing the flow speed to 3 m/s hindered the spread because flame fluttering increases, convective cooling increases, and the burned gas resident time becomes smaller. Thus, the critical spacing is decreased as seen in Fig. 3.

3.2. Fire spread rate

Using the method described in section 2.2, the ignition times for each spacing and velocity case were extracted from the fire spread video data. Each experimental case was repeated five times to ensure repeatability. The averaged ignition times for each dowel position in the array are plotted in Fig. 4. The shaded regions indicate the range of the experimental results. Although some cases have better repeatability to others, there exists a wide range of the results due to the nature of stochastic fire behaviors similarly observed in other studies [6,7]. The data is arranged such that the $t = 0$ s corresponds to ignition of the dowel following the pilot dowel.

Due to observed non-linearities in the results, especially in the later stages of the spread and in larger spacing configurations, a quadratic regression was fit to the data in order to compare the results. The minimum regression R^2 value for all the cases was 0.98. Taking the derivative of the regression equations, the average rate of spread at the time of specific dowel positions can be evaluated. The spread rates for dowel positions 3, 5, and 7 are shown in Fig. 5. These three dowel positions represent the early, mid, and late stages of fire spread along the array.

It is expected that increasing the flow speed will increase the spread rate due to increased flame tilting and convective heat transfer. However, Fig. 5 shows this is not always the case. Specifically, the cases of 1 and 1.15 cm spacing show faster spread rate under a 2 m/s freestream velocity compared with 3 m/s. It should be noted that although 1 and 1.15 cm spacings have a faster spread rate at 2 m/s, only the 1 cm case

has an overall faster fire spread at 2 m/s than 3 m/s as seen in Fig. 4. It would also be expected that smaller spacings between dowels result in the faster flame spread because of reduced distance that the flame must overcome to contact the next array element. Indeed the 0.5 cm spacing condition exhibits the fastest spread rates, but the 0.75 cm spacing spread rates under 2 and 3 m/s wind conditions are comparable to the 0.5 cm case, at most within 8–9% of the 0.5 cm rates despite the increased distance between dowels. Similar trends are seen in the flame propagation under a 1 m/s wind, which seems to be only slightly affected by the increasing spacing, as compared to higher flow speeds. Higher flame buoyancy effects at 1 m/s coupled with the slow flow speed create the biggest flame area of the three velocities, which could contribute to the decreased effects spacing has on the flame spread. However, a large part of the flame is directed upwards in contrast to the other two flow speeds leading to slower spread overall when compared to faster flow speeds. There is a consistent drop in the spread rates throughout the three stages of fire spread when the spacing is increased to 1 cm or greater. Note that 1 cm is the critical spacing for the no flow condition, or where marginal flame propagation is observed as shown in Fig. 3.

Studies on the fluid mechanics of tandem cylinders in crossflow show the existence of various wake flow regimes, and it could be used to explain the observed fire spread rate behavior [23–25,28,29]. When cylinders are placed in a tandem array, the wake and corresponding vortical structures are dictated by cylinder spacing and Reynolds number (Re). The spacing and Re used in this study correspond to the conditions outlined in literature [24,25], in which a significant change in the vortex shedding pattern was observed. The increased spacing between cylinders and faster flow speed lead to the wake vortex shedding affecting the inter-cylinder region rather than extending past the downstream cylinder. The size and fluctuations of the wake and vortex structures could act to inhibit or hinder fresh air entrainment and mixing from the surrounding freestream flow into the reaction zone. Under favorable fire spread conditions, air entrainment results in partially-premixed conditions leading to a higher flame temperature. The increased flame temperature enhances heat transfer and compensates the convective cooling due to the entrained cold air. At unfavorable conditions, the induced vortical structures block fresh air entrainment to the reaction zone. Consequently, combustion reactions occur at rich conditions reducing the flame temperature. Furthermore, increased

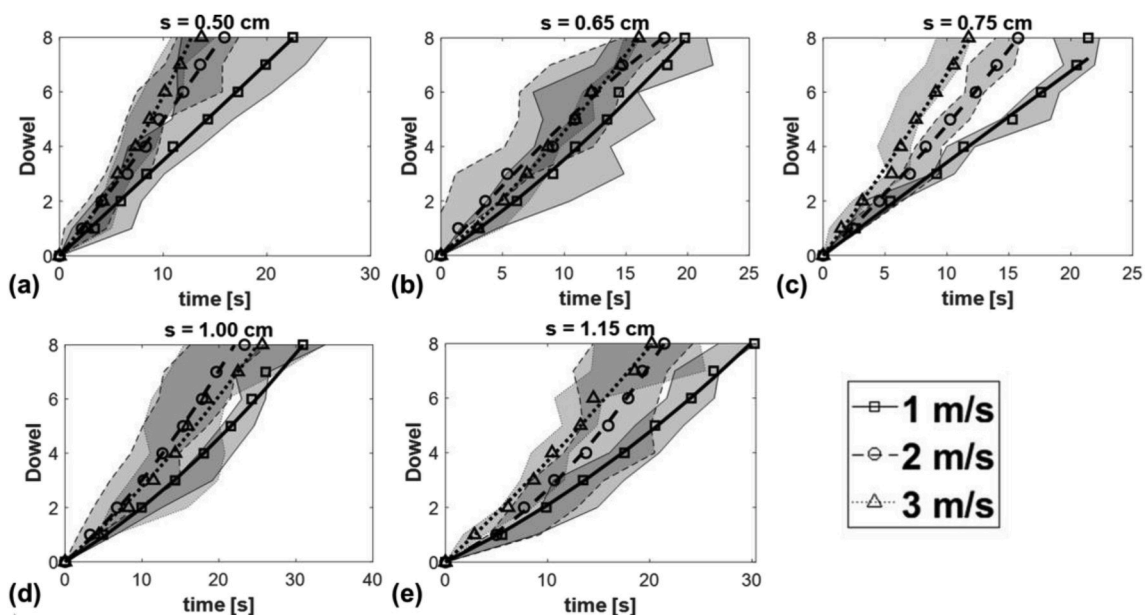


Fig. 4. Fire spread for (a) 0.50, (b) 0.65, (c) 0.75, (d) 1.00, and (e) 1.15 cm spacings under 1, 2, and 3 m/s freestream flows. The markers are averages of 5 data points with the experimental range shown as the shaded region. The plotted line represents a quadratic regression of the data points.

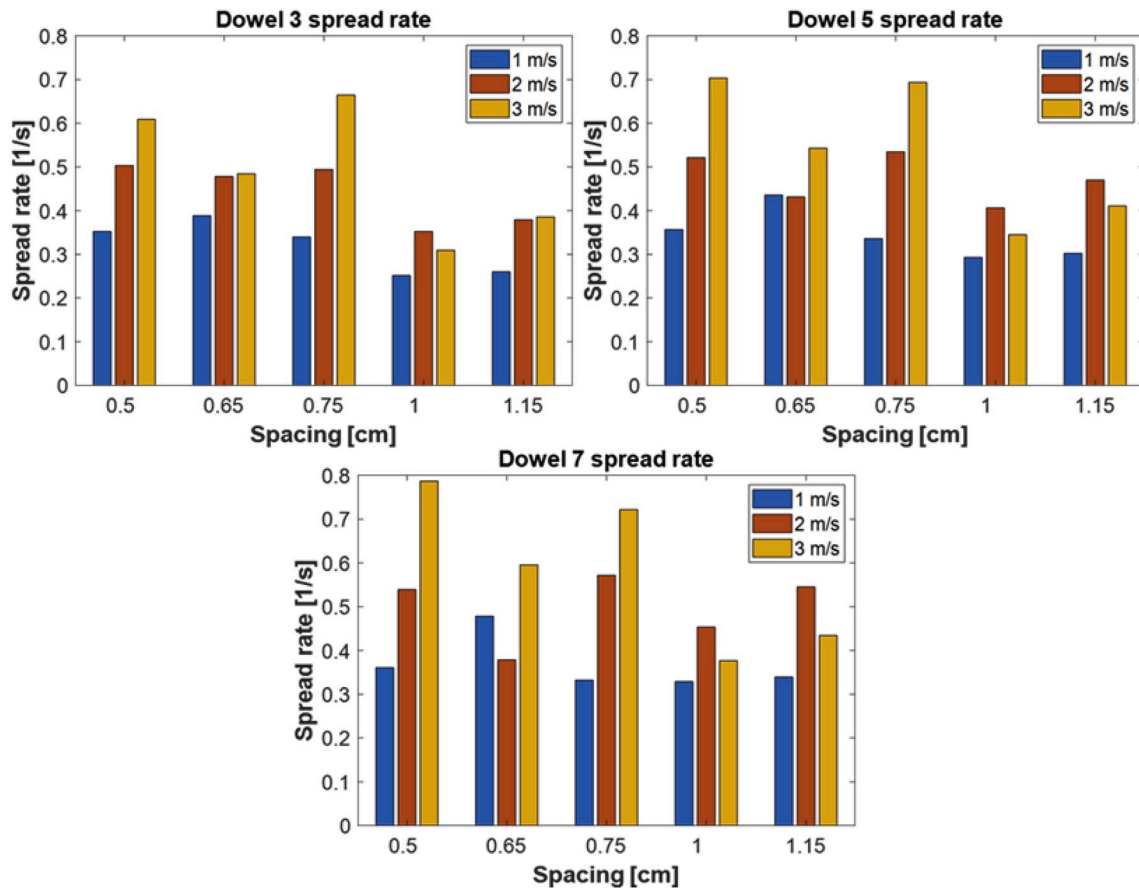


Fig. 5. Fire spread rate at dowel positions 3, 5, and 7 for multiple spacings under 1, 2, and 3 m/s freestream flows.

velocity accompanies convective cooling from the surrounding cold air. The reduction in flame temperature from less partially-premixed conditions and increased convective cooling could hinder the flame spread and lead to longer ignition times. More discussion will be provided in the later sections by analyzing flame visualization.

3.3. Flame visualization

Although the spread rate analysis gives some insight into the fire spread behavior, the deviations from expected behaviors need further explanation. These deviations are mainly the drop off in spread rate at spacings greater than 0.75 cm and the subsequent acceleration of the fire propagation under 2 m/s flow that generates faster fire spread than the

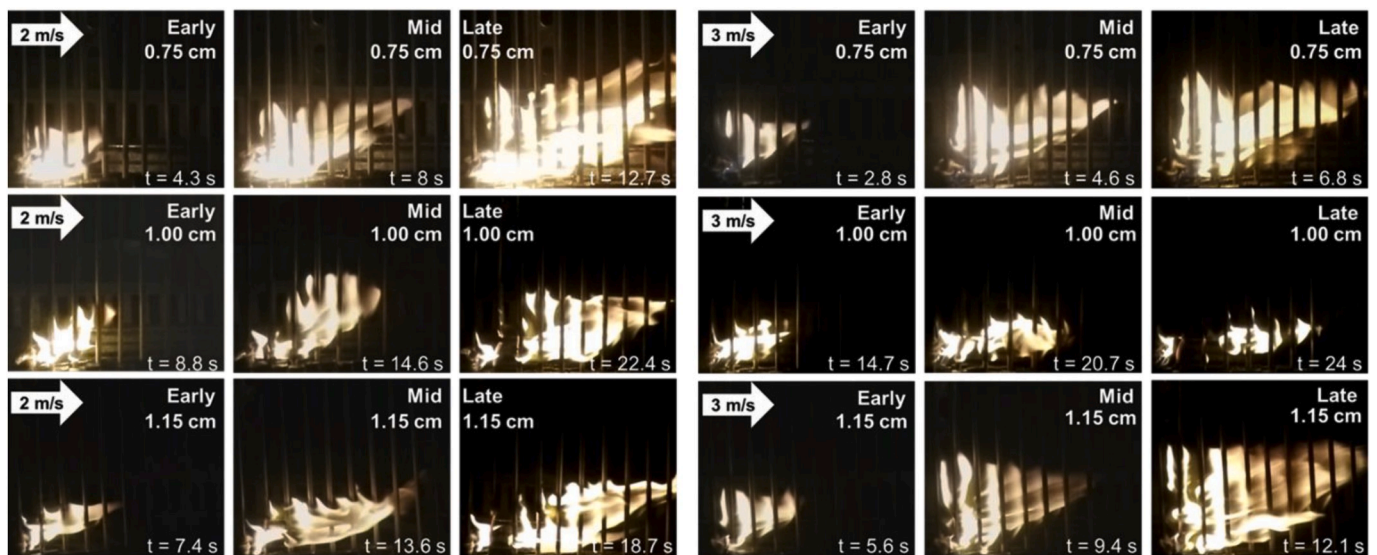


Fig. 6. Images of early, middle, and late stage fire spread at 0.75–1.15 cm spacings for 2 and 3 m/s. Early stage images are taken at the ignition of dowel 3. Mid stage images are at the ignition of dowel 5. Late stage images are taken at the ignition of dowel 7.

3 m/s case. To provide further understanding, direct flame images were compared. Fig. 6 shows representative images from the fire spread experiments at the time of ignition of dowel positions 3, 5, and 7 representing the early, middle, and late stages of fire spread along the array, respectively. It should be noted that the early, middle, and late stages are not the same for each spacing and flow speed condition. They represent stages of the fire spread for each tested condition. The actual time of ignition is marked in each picture in Fig. 6. Images of the 0.75, 1, and 1.15 cm spacing arrays are presented for 2 and 3 m/s. It should be noted that the fire spread could be affected by initial ignition processes. Thus, to maintain the consistency in experiments, the ignition methods was kept consistent for all experiment, and the experiments were repeated to ensure repeatability.

At 1 cm spacing, it seems that the fire spread at 2 m/s is the more vigorous spreading case than that at 3 m/s. At 2 m/s, the flame is slightly segmented by each dowel, but the flame is largely merged. As the flame spreads downstream, the flame grows and engulfs multiple dowels simultaneously (mid-stage). Eventually, a large merged flame is observed in the late stage, with the earliest dowels burned through. In contrast, at 3 m/s, early in the fire spread the flames are like the 2 m/s but markedly slower, suggesting that the effects of the flow are present in the 2 m/s case but not as prevalent. The flame structure becomes more fragmented instead of merging as the flames move to the middle stages of the array. Towards the end of the array, the flames remain small and almost seem to burn independent of each other. In contrast, at the 2 m/s case the fire includes 6 burning dowels contributing to the overall flame. At 3 m/s, it seems that the flow confines the flame close to each ignited dowel instead of aiding the flame to contact the next unignited dowel. The flame confinement then slows down the overall fire spread. Although most prevalently seen in the 1 cm case, the flame confinement may be present for all spacings at 3 m/s since the upward flame spread along each dowel at other spacings is greater compared to 2 m/s, suggesting a longer residence time at each dowel position.

Flame images also show significant flame behavior changes from 0.75 cm to 1.15 spacings. As discussed in the previous section, a spacing change from 0.75 cm to 1 cm causes a significant decrease in a spread rate, and at 1.15 cm spacing, the flame spread is comparable or faster than those at 1 cm spacing. It would be expected that the 3 m/s behavior would be similar to that of the 1 cm case at 1.15 cm. However, the flame at 1.15 cm spacing resembles the 0.75 cm case instead, as seen in Fig. 6.

From the flame images (Fig. 6), the 1 cm spacing case shows unique flame behavior in response to the higher flow speed of 3 m/s. At 2 m/s the flame created at the 1 cm condition resembles that of the other spacings. The flow tilts the flame and creates an oblong shape stretching in the downstream direction. In contrast, at a flow speed of 3 m/s the flame shape is completely changed for the 1 cm condition in comparison to the flames at other spacings. Additionally, the 0.75 cm cases have the most intense flames in comparison. It seems that the flow has multiple effects; tilting the flame and increasing the flame contact surface to dowels and inducing the vortex shedding around the dowel cylinders

which change the mixing conditions (air entrainment) in the inter-cylinder region. The vortices also are interacting with the flame itself to either confine or stretch the flame and increasing or decreasing the heat delivered to unignited dowels. Although it is not the focus of the current study, flow field measurements could provide further details for the vortex shedding effects on the fire spread behaviors.

3.4. Cylinder wake frequency measurements

By performing a discrete Fourier transform (DFT) of the pressure data collected from the pitot probe measurements, characteristic peaks may reveal pressure fluctuation oscillations related to the vortex shedding. Fig. 7 shows the DFT for the 1 cm spacing case. At 1 m/s flow speed, there is a slight peak around 30 Hz. A peak develops around 35 Hz when the velocity is increased to 2 m/s indicating slow but persistent oscillations in the pressure measurements at that frequency. Once the velocity is increased to 3 m/s, the 35 Hz peak remains, with a second peak around 75 Hz and a third smaller peak at approximately 250 Hz. The presence of the additional peaks at 3 m/s could be evident of faster or more aggressive vortex-induced oscillations. As discussed previously, the higher frequency oscillations together with array spacing variations could combine to provide faster flame propagation, as seen in the 0.75 cm case, or hinder and quench the flames, seen in the 1 cm spaced array when subject to a 3 m/s flow. Although these flow measurements are preliminary and not the focus of the current study, further investigation of the flow field is underway that could provide insight on the vortex shedding effects on the fire spread behaviors.

Although it is preliminary, changes in shedding frequencies could be explained by Re and Strouhal number (St) relations [30]. Re calculated based on the dowel diameter freestream air for 1, 2, and 3 m/s flow speeds are 203, 406, and 610, respectively. Corresponding St of a cylinder for $Re = 203, 406, \text{ and } 610$ are approximately 0.17, 0.18, and 0.20 (from Fig. 3 in Ref. [30]). Thus, the characteristic frequencies of the wake for 1, 2, and 3 m/s flow speeds are calculated as 5.3, 11.3, and 18.8 Hz, respectively. The discrepancies between the measured and estimated frequencies could be caused by different dowel settings. Since the current study used an array instead of a single cylinder, the shedding characteristics could be shifted. However, the tendency of increasing shedding frequency for a higher flow speed remains the same.

The regime of vortex shedding for $Re = 203, 406, \text{ and } 610$ is the transition range [30]. For $Re = 203$, the vortex is in transition rage, and the vortex street becomes fully turbulent for $Re = 406$ and 610. Thus, mixing is enhanced as Re increases, and a spread rate increases (see Fig. 5). However, when the spacing is long enough (beyond 1 cm), mixing by vortex shedding increases cooling by bringing more cold freestream air into the reaction zone, which reduces the gas temperature and spread rate. Furthermore, enhanced mixing results in a further decrease in gas temperature due to the increased cooling. This enhanced mixing and cooling effects could describe the inversion fire spread rate between 2 and 3 m/s at 1 cm spacing. With further experiments and

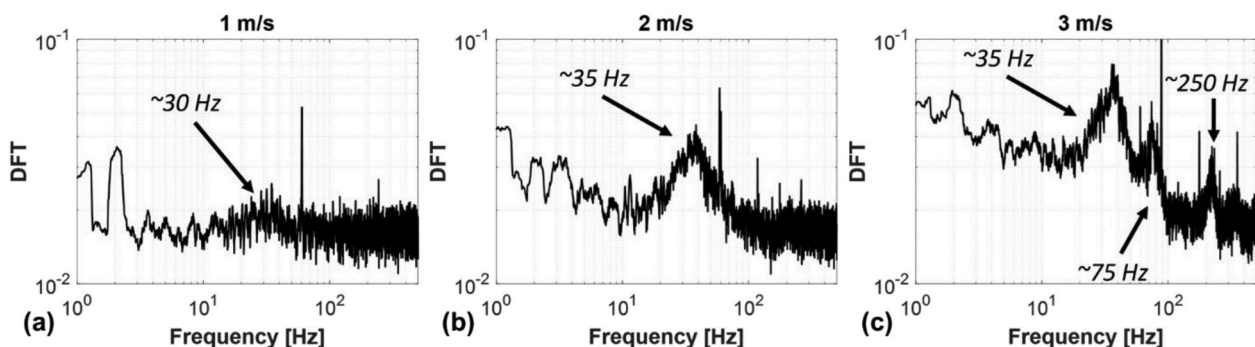


Fig. 7. Discrete Fourier transform (DFT) of pressure signal behind array at 1 cm spacing for (a) 1, (b) 2, and (c) 3 m/s flows.

measurements, a more rigorous thermal and fluid dimensional analysis will be possible in the future.

4. Conclusions

The fire spread behavior along a suspended array of wooden dowels was investigated for a range of spacings (0.5, 0.65, 0.75, 1, and 1.15 cm) and wind speeds (1, 2, and 3 m/s). The spread rate for all cases was modeled with quadratic regressions due to slight flame spread acceleration. At fixed spacings, the spread rate generally increases with faster flow speeds. However, deviations from expected propagation behavior occur. Namely, at the 1 cm spacing conditions, the faster spread is observed when subjected to a flow of 2 m/s rather than 3 m/s, in contrast to the other spacing conditions. Furthermore, increasing the spacing between dowels does not always lead to slower ignition times, with the 0.75 cm spacing cases showing spread rates comparable to those of 0.5 cm at 2 and 3 m/s flow speeds. Flame visualization showed smaller discrete flames formed in the 1 cm spacing array when subjected to a 3 m/s flow. The higher frequency vortices measured with pitot probes developed from each dowel cylinder are changing the gaseous mixing conditions as well as stretching or constricting the flame in a way that fluctuates the heat transfer. As a consequence, there exists a shift in the spread rate trend between the 0.75 cm and 1 cm spacings. Flow effects seemed to be minimal for the spacings below 0.75 cm. At 0.75 cm spacing, the mixing and flow conditions are such that an optimal combination is achieved leading to fire propagation as fast as the 0.5 cm spacing cases. Once past 0.75 cm spacing, the fire spread was slowed down significantly. In the future, flow field measurements around the cylinder array will be performed to further investigate the confined fire behaviors at 1 cm spacing at 3 m/s and reduced spread rates at 1 cm spacing. A more refined study of the flame behavior at fixed spacings with gradually increased flow speeds should identify clearer trends in the flame propagation behavior need to be conducted. Additionally, turbulence intensity measurements at select points in the array should characterize the changes in the mixing behavior as flow speed is varied. Lastly, experiments with arrays of more fuel elements will be conducted in order to fully characterize the nonlinearities observed in the fire spread.

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.

Acknowledgments

This work was supported by U.S. DOD/EPA/DOE Strategic Environmental Research Development Program (SERDP, Project Number: RC-2641) for study design, data collection, analysis and interpretation, and writing. Seong-kyun Im was supported by Korea University research grants for writing the paper.

References

- [1] W.L. Fons, Analysis of fire spread in light forest fuels, *J. Agric. Res.* 72 (1946) 93–121, <https://doi.org/10.1016/j.jns.2003.09.014>.
- [2] H.W. Emmons, T. Shen, Fire spread in paper arrays, *Symp. Int. Combust.* 13 (1971) 917–926, [https://doi.org/10.1016/S0082-0784\(71\)80092-9](https://doi.org/10.1016/S0082-0784(71)80092-9).
- [3] M. Vogel, F.A. Williams, Flame propagation along matchstick arrays, *Combust. Sci. Technol.* 1 (1970) 429–436, <https://doi.org/10.1080/00102206908952223>.
- [4] J.M. Prah, J.S. Tien, Preliminary investigations of forced convection on flame propagation along paper and matchstick arrays, *Combust. Sci. Technol.* 7 (1973) 271–282, <https://doi.org/10.1080/00102207308952367>.
- [5] M.F. Wolff, G.F. Carrier, F.E. Fendell, Wind-aided firespread across arrays of discrete fuel elements. II. Experiment, *Combust. Sci. Technol.* 77 (1991) 261–289, <https://doi.org/10.1080/00102209108951731>.
- [6] M.J. Gollner, Y. Xie, M. Lee, Y. Nakamura, A.S. Rangwala, Burning behavior of vertical matchstick arrays, *Combust. Sci. Technol.* 184 (2012) 585–607, <https://doi.org/10.1080/00102202.2011.652787>.
- [7] L. Jiang, Z. Zhao, W. Tang, C. Miller, J.H. Sun, M.J. Gollner, Flame spread and burning rates through vertical arrays of wooden dowels, *Proc. Combust. Inst.* (2018) 1–8, <https://doi.org/10.1016/j.proci.2018.09.008>, 000.
- [8] C.H. Miller, M.J. Gollner, Upward flame spread over discrete fuels, *Fire Saf. J.* 77 (2015) 36–45, <https://doi.org/10.1016/j.firesaf.2015.07.003>.
- [9] R.O. Weber, A model for fire propagation in arrays, *Math. Comput. Model.* 13 (1990) 95–102, [https://doi.org/10.1016/0895-7177\(90\)90103-T](https://doi.org/10.1016/0895-7177(90)90103-T).
- [10] T. Beer, Fire propagation in vertical stick arrays: the effects of wind, *Int. J. Wildland Fire* 5 (1995) 43–49, <https://doi.org/10.1071/WF950043>.
- [11] D. Weise, G. Biging, Effects of wind velocity and slope on fire behavior, *Fire Saf. Sci.* 4 (1994) 1041–1051, <https://doi.org/10.3801/IAFSS.FSS.4-1041>.
- [12] H.W. Emmons, Fire in the forest, *Fire Res. Abstr. Rev.* 5 (1963) 163–175.
- [13] M. Vogel, F.A. Williams, Flame propagation along matchstick arrays, *Combust. Sci. Technol.* 1 (1970) 429–436, <https://doi.org/10.1080/00102206908952223>.
- [14] J.M. Prah, J.S. Tien, Preliminary investigations of forced convection on flame propagation along paper and matchstick arrays, *Combust. Sci. Technol.* 7 (1973) 271–282, <https://doi.org/10.1080/00102207308952367>.
- [15] H.W. Emmons, Fundamental problems of the free burning fire, *Symp. Int. Combust.* 10 (1965) 951–964, [https://doi.org/10.1016/S0082-0784\(65\)80238-7](https://doi.org/10.1016/S0082-0784(65)80238-7).
- [16] F.J. Kosdon, F.A. Williams, C. Buman, Combustion of vertical cellululosic cylinders in air, *Symp. Int. Combust.* 12 (1969) 253–264, [https://doi.org/10.1016/S0082-0784\(69\)80408-X](https://doi.org/10.1016/S0082-0784(69)80408-X).
- [17] L. Jiang, Z. Zhao, W. Tang, C. Miller, J.H. Sun, M.J. Gollner, Flame spread and burning rates through vertical arrays of wooden dowels, *Proc. Combust. Inst.* (2018) 1–8, <https://doi.org/10.1016/j.proci.2018.09.008>, 000.
- [18] M.F. Wolff, G.F. Carrier, F.E. Fendell, Wind-aided firespread across arrays of discrete fuel elements. I. Theory, *Combust. Sci. Technol.* 77 (1991) 261–289, <https://doi.org/10.1080/00102209108951731>.
- [19] F.R. Steward, L.J. Wuest, R.T. Waibel, Some characteristics of fires within uniform fuel matrices, *Heat Transf. Div. Pap.* (1977). ASME 77-HT-71.
- [20] I. Harimi, M. Saghafian, Numerical simulation of fluid flow and forced convection heat transfer from tandem circular cylinders using overset grid method, *J. Fluid Struct.* 28 (2012) 309–327, <https://doi.org/10.1016/j.jfluidstruct.2011.12.006>.
- [21] H. Nakamura, T. Igarashi, Variation of Nusselt number with flow regimes behind a circular cylinder for Reynolds numbers from 70 to 30000, *Int. J. Heat Mass Tran.* 47 (2004) 5169–5173, <https://doi.org/10.1016/j.ijheatmasstransfer.2004.05.034>.
- [22] W.A. Khan, J.R. Culham, M.M. Yovanovich, Fluid flow around and heat transfer from an infinite circular cylinder, *J. Heat Tran.* 127 (2005) 785, <https://doi.org/10.1115/1.1924629>.
- [23] Y. Zhou, M.W. Yiu, Flow structure, momentum and heat transport in a two-tandem-cylinder wake, *J. Fluid Mech.* 548 (2006) 17–48, <https://doi.org/10.1007/s10016-005-9282-2>.
- [24] B.S. Carmo, J.R. Meneghini, S.J. Sherwin, Secondary instabilities in the flow around two circular cylinders in tandem, *J. Fluid Mech.* 644 (2010) 395, <https://doi.org/10.1017/S0022112009992473>.
- [25] B.S. Carmo, J.R. Meneghini, S.J. Sherwin, Possible states in the flow around two circular cylinders in tandem with separations in the vicinity of the drag inversion spacing, *Phys. Fluids* 22 (2010) 1–7, <https://doi.org/10.1063/1.3420111>.
- [26] Y. Zhang, J.H. Sun, X.J. Huang, X.F. Chen, Heat transfer mechanisms in horizontal flame spread over wood and extruded polystyrene surfaces, *Int. J. Heat Mass Tran.* 61 (2013) 28–34, <https://doi.org/10.1016/j.ijheatmasstransfer.2013.01.069>.
- [27] J.G. Quintiere, Fundamentals of Fire Phenomena, John Wiley & Sons Ltd, 2006, <https://doi.org/10.1002/0470091150>.
- [28] G.V. Papaioannou, D.K.P. Yue, M.S. Triantafyllou, G.E. Karniadakis, Three-dimensionality effects in flow around two tandem cylinders, *J. Fluid Mech.* 558 (2006) 387–413, <https://doi.org/10.1017/S0022112006000139>.
- [29] C.M. Sewatkar, R. Patel, A. Sharma, A. Agrawal, Flow around six in-line square cylinders, *J. Fluid Mech.* 710 (2012) 195–233, <https://doi.org/10.1017/jfm.2012.359>.
- [30] J.H. Lienhard, Synopsis of Lift, Drag, and Vortex Frequency Data for Rigid Circular Cylinders, Technical Extension Service, Washington State University, Pullman, WA USD, 1966.