PHYS 6268

Final Report

Lezheng Fang

# Fire-front modelling in a discrete match system

Team: Lezheng Fang, Ben Musci, Mateo Reynoso

# Table of content

# 1. Introduction

Forest wildfire, induced by human behavior or naturally triggered, occurs in different scales world widely. In recent years, large scale fires have become much more active around the globe and post significant threats to human lives and properties, which lead to needs of fine wildfire models to prevent and contain the destructive wildfires.

Some early work of wildfire modeling in nonlinear physics can be traced back to Bak *et al*. [1], who present a probabilistic cellular automation model highlighting fractal energy dissipation and self-organized critical state. Later, computer-aided technology allows greater complexity of numerical modelling and computation, and thus researchers start to investigate the spread of wildfire in a more quantitative method [2]. Among this studies, a number of factors affecting the wildfire propagation, including firebrands [3], atmospheric interaction [4, 5] and topographic interaction [6] have been explored and discussed in large-scale systems. Due to the unstable and chaotic nature of wildfire, majority of these study are based on theory and numerical simulations.

Inspired by [7], in this work, we propose an experimental study of a one dimensional match array simulating a 1D forest, and report strong correlation between the fire-front propagation velocity and match spacing as well as the inclination angle. The match spacing in 1D system can be linked to the woods density in a 2D forest, which is a key parameter in determining fire propagation and pattern formation. The inclination angle represents the local topography of a forest, and the study of which offers insights to uphill/downhill wildfire propagation. In both parameter study, we offer quantitative measure of the fire-front propagation velocity, using a new velocity measuring framework leveraging a “flame flickering” phenomenon. This “flame flickering” phenomenon in the match system may well relate to wildfires at certain types of forest, and have great potentials in monitoring wildfires in these areas. Additionally, we document a few new phenomenon in match systems that may relate to small scale wildfire in extreme conditions.

# 2. Experimental Setup

As depicted in Fig. 1, we set up a number of wooden matches on a flat plastic board which represents the forest terrain. The plastic board can be placed flat or with an inclination angle, which is calculated via the total length of the board and its horizontal projection length read on the ruler. We measure and draw grids on the plastic board to ensure the spacing of matches are roughly the same for each trial experiment.

We insert each match perpendicular to the board and leave roughly the same length in the air, so that the fire propagation line will stay parallel to the terrain. For each trial experiment, we ignite one end of the match array with a long-handle gas lighter, and capture the dynamics with a phone camera fixed on the desk. The camera is kept around

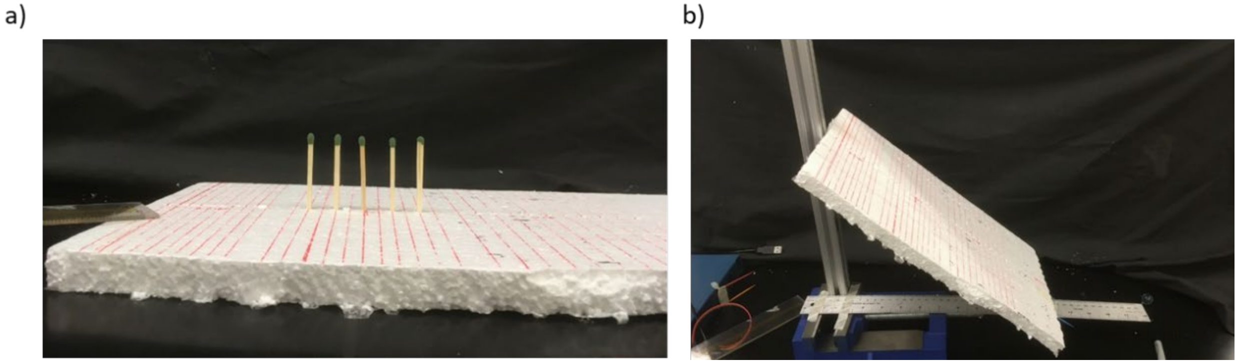

Figure 1. The experimental setup for fire propagating study at a) flat surface b) inclined surface.

15 inches away from the experiment and properly oriented to ensure minimal geometry-induced graph distortion.

Normally one trial experiment finishes before the fire on any match reaches the bottom and melt the plastic. However, to avoid this situation in some special cases, we use a water dropper to extinguish the fire on matches burned down to the bottom.

In this study, we vary the spacing from $6.5mm$ to $10mm$ and inclination angle from 9 $deg$ to 60 $deg$ to investigate their effects on whether the fire can propagate, how fast the fire propagates, and some detailed dynamics.

## 3. Data Acquisition and Analysis

The dynamics of fire propagation in the matches are captured in videos. These videos are then converted into gray scale videos, for flame recognition. We use the MATLAB feature *imgaussfilt* to remove certain background noise, and manually select the most informative region regarding the fire propagation to reduce the computation complexity, as shown in Fig. 2a-c. Since the video is in gray scale, each pixel is associated with one single value featuring its color, we compute the center of the flame by using an algorithm analogous to center of mass computation,

$$\bar{X} = \frac{\sum_i c_i P_{xi}}{\sum_i P_x} \tag{1}$$

$$\bar{Y} = \frac{\sum_i c_i P_{yi}}{\sum_i P_{yi}} \tag{2}$$

where $\bar{X}$ and $\bar{Y}$ denotes the horizontal and vertical coordinates of the center of the flame, and $P_{xi}, P_{yi}$ and $c_i$ represent the horizontal and vertical coordinates and the color of the

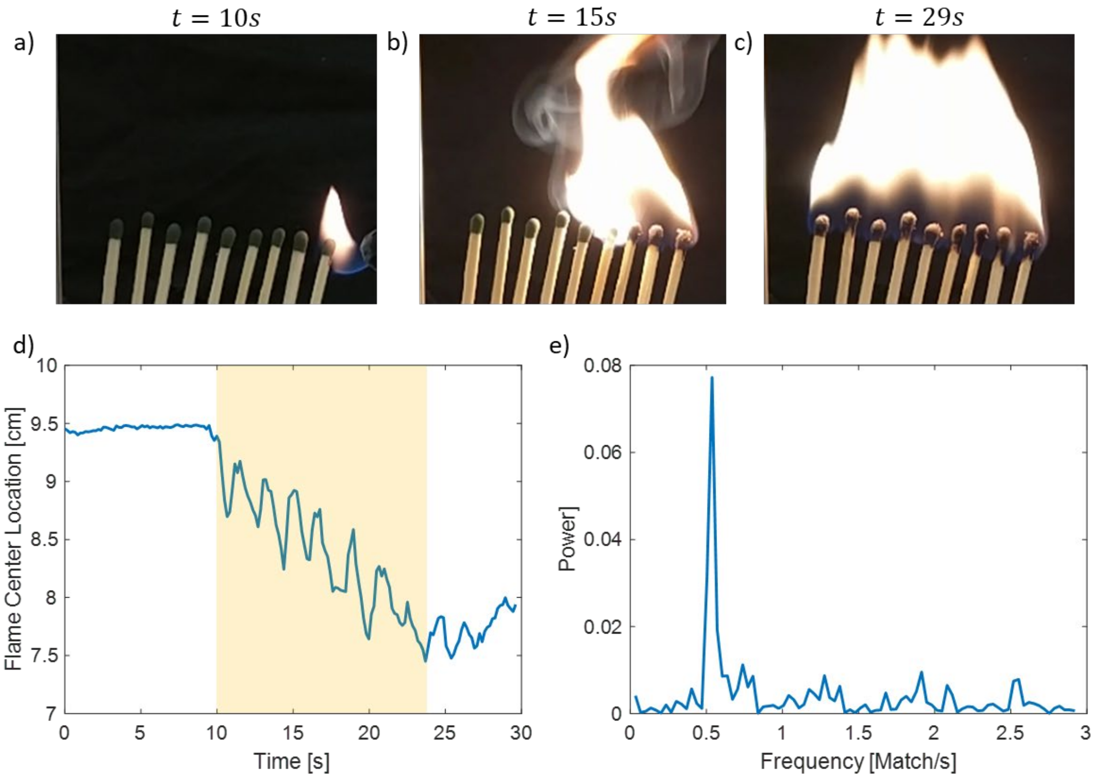

Figure 2. Video processing and velocity measurement. a)-c) The time response of fire propagation at $\alpha = 9.5\ degree$ with spacing $d = 6.5mm.$ d) The time response of the center of the flame. e) The FFT result of the velocity of the flame-center highlighted in part d.

$i^{th}$ pixel. As such, we depict the trajectory of the flame center in time, see Fig. 2d for an example.

One distinct yet robust signature we observe in these trajectories is a "flame flickering" phenomenon during the propagation, i.e. the flame center fluctuates whenever a new match in the array is ignited. With the detailed phenomenon and explanation discussed in next section, here we confine our interest in a method to measure the speed of fire-front leveraging this phenomenon.

The highlighted region is Fig. 2d represents the fire-propagating duration. We first conduct a numerical derivative on the highlighted response with respect to time, resulting a fluctuated center velocity in time. A Fast-Fourier-Transformation (FFT) on the velocity then reveals the periodicity of such "flame flickering", indicating the frequency $f$ of new match being ignited, as illustrated in Fig. 2e. The inverse of this frequency yields the average time the fire propagates between two matches $\Delta t$. Thus, the speed of fire-front, at known spacing $d$, can be obtained from the equation below,

$$v = \frac{d}{\Delta t} = \frac{d}{\frac{1}{f}} = df. \tag{3}$$

We also calculated the velocity in a more traditional way by capturing the flame edge, and compare it with above approach. As illustrated in Fig.3, the average velocity measured follows a linear relation with the flickering frequency, which agrees with our theory above.

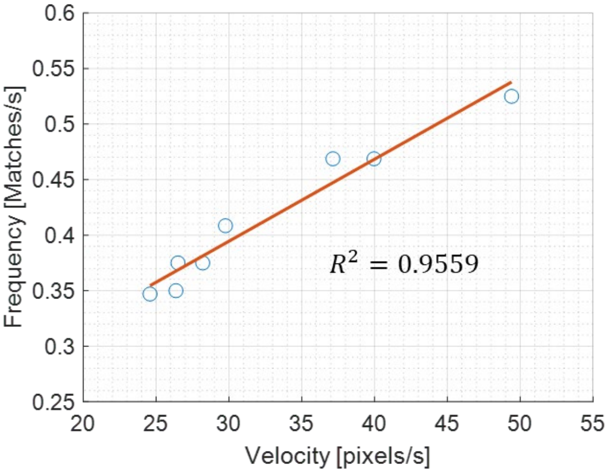

Fig. 3. Comparison of flame flickering frequency and flame-front velocity.

# 4. Results

## 4.1 Flame Flickering

As introduced in last section, we observe a rather bizarre phenomenon during fire propagation in match array and termed it flame flickering. Revisiting Fig. 2d, we see the center of the flame seem to be pushed back whenever the next neighbor match starts to burn. This phenomenon is robust and we observe it in all our experiments when we place the match head with the chemical coating up. However, when we reverse each match and place its uncoated tail up for fire propagation, this flickering phenomenon is much less pronounced. This leads to a hypothesis that links the flickering phenomenon to the chemical coating.

In general, the chemical coating on the head of modern match is composed of white phosphorus or phosphorus sesquisfide and potassium chlorate or equivalent chemicals. The former chemical has a relatively low burning point, and the ignition can be triggered by friction. The increasing temperature shortly triggers the thermo-decomposition of the latter chemical which not only further increases the temperature but releases oxygen as a reaction product. Thus, the ignition of each match can be recognized as a small-scale explosion. The blow resulted from thermal expansion and released oxygen may thus account for the push-back and flickering of the propagating flame.

Despite the fact that forests in nature does not have such engineered combustion-support coating, there are trees that contains rich flammable secretion. If these trees are quasi-periodically distributed in a forest, one may expect similar flickering effect on the wildfire, which may offer valuable information about fire propagating speed and orientation etc.

## 4.2 Fire propagation on flat surface

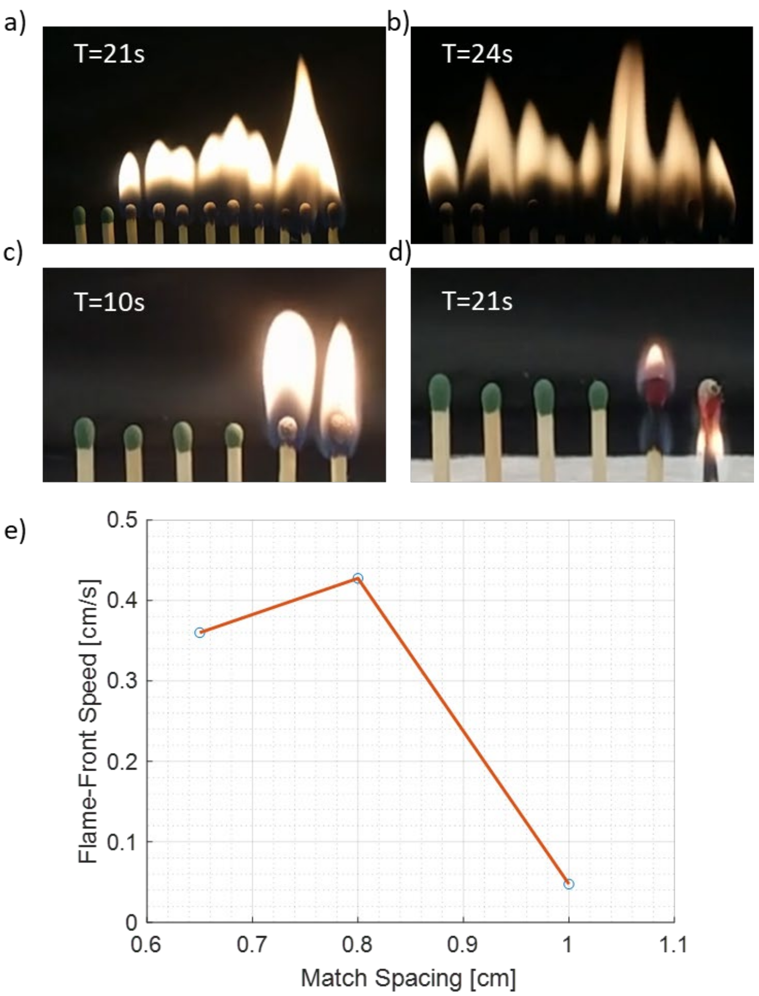

Fig. 4 Fire propagation in different spacing on flat surface a) - b) Snapshot of the fire propagation at different instant with spacing $d = 0.8cm$. The propagation is right-to-left c) - d) Snapshot of the fire propagation at different instant with spacing $d = 1cm$. The propagation is right-to-left e) The average speed of fire-front propagation at different spacing.

In this section, we investigate how the spacing between matches affect the propagation of fire on a flat surface. Three spacing distances, $6.5mm, 8mm$ and $10mm$, are selected. For each of them, we conduct multiple trial experiments and take the average velocity to minimize the error.

In Fig. 4a-b, we show two snapshots of an experiment with spacing $d = 0.8cm$. The fire is able to propagate from right to left and ignite two matches in roughly three seconds. In Fig, 4c-d, at a larger spacing $d = 1cm$, the fire propagates from the first match on the right to the second but then remains localized at the right two matches. This phenomenon indicates there could be bifurcation spacing $8cm < d^* < 10cm$ that determines whether or not the fire propagates along the array. However, it is of great challenge to further quantify this threshold value for two reasons: i) the individual difference of each match and the spacing control method we employ restricts the resolution of the spacing measurement; ii) there seems to be two different mechanism that propagates the fire to the next match, and thus a single critical spacing may not be sufficient to describe the dynamics.

We term the two types of propagating the fire “fast” and “slow” propagation. The “fast” propagation usually occurs at small spacing array, where the ignition of an individual match starts with a relatively large flame that contains its neighboring match in and thus ignites it in a very short time. Given a fixed spacing, this “fast” propagation results a relatively constant ignition rate, in unit of match per second, which is independent to the spacing itself. In the experiment, we observe the “fast” propagation is usually associated with the phenomenon that the flames of each match tends to join together and form a larger flame, as shown in Fig. 4a-b.

The “slow” method generally occurs when the spacing is larger, such that the initial ignition flame of a single match cannot contain its neighboring matches and do not ignite them immediately. As the fire burns down a match, there is a possibility it would “magically” ignite its neighboring match. While the detailed mechanism of “slow” propagation remains uncovered, here we provide our two hypothesis for this phenomenon: i) at a larger spacing, the neighboring match receives heat mainly from radiation instead of convection, and such radiation heat requires a longer time to accumulate; ii) as the fire burns down a match, the high-temperature (upper half) region of the flame also shifts down, and the ignition of neighboring match occurs when the head of the neighboring match is sufficiently close to the high-temperature region of the flame. In the experiment, the time it takes for fire to “slow” propagate between matches seems rather random, and the velocity of the “slow” propagation is not constant. A key feature for this “slow” propagation is that each match maintains its individual flame lobe, as depicted in Fig. 4c-d.

Finally, in Fig. 4e, we present the average flame-front speed measured via the method introduced in the previous section. The average flame front speed raises as the spacing increases from 0.65cm to 0.8cm. We believe this is in the regime of “fast” propagation where the ignition rate is relatively independent of the spacing, indicating the overall velocity is proportional to the spacing. At spacing$d = 1cm$, we observe a very slow fire-front speed. At this spacing, fire tends to remain localized and does not propagate. Some occasional propagation occurs rather random and takes relatively long time, which we categorizes it to the “slow” propagation phenomenon.

Overall, the results suggest that for a 1D forest, within the “fast” propagation limit, the larger the spacing of trees are, the faster the fire propagates. However, outside the “fast” propagation limit, the fire propagation becomes slow and in a rather random rate. Note that, this result may not directly apply to forest in nature, as we neglect a nonlinear effect that fire clusters in 2D may result a much more concentrated fire zone which radiates heat in a much larger power, yet the discussion on “fast” and “slow” propagation offers important insight into the micro- dynamics of fire propagation, which is of great significance to forest density control in order to prevent wildfire spread.

### 4.3 Fire propagation on inclined surface

In this section, we explore the effects of inclined terrain on fire propagation. As depicted in Fig. 5a, a number of matches are positioned perpendicular to an inclined surface with spacing $d$ and inclination angle $\alpha$. Five inclination angles, $9, 25, 40, 50, 60$ degrees and the same three spacing as in last sections are chosen, and we plot the resultant fire-front velocity in Fig. 5b. Note that, in the experiment we always excite the system from the lowest match, and only study the uphill fire propagation. The direction of fire-front velocity is along the inclined surface.

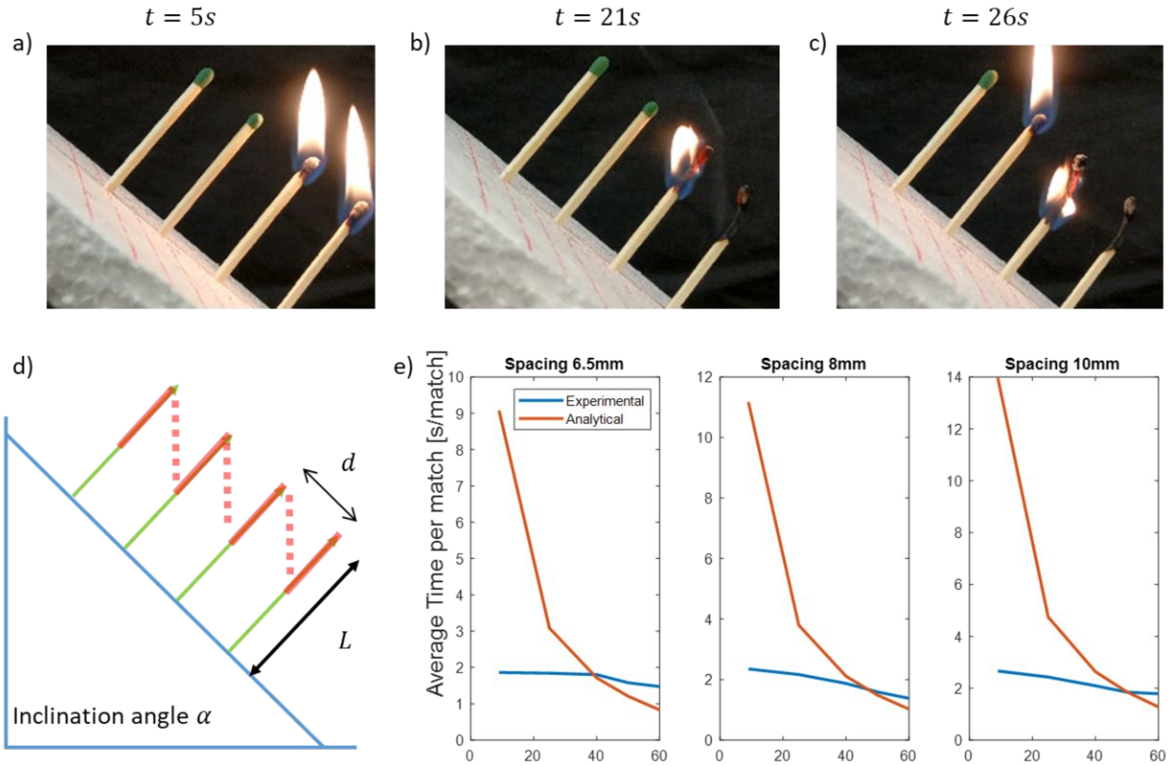

Figure 6. a)-c) Snapshot of the fire propagation at different instant with spacing $d = 2cm$ at $\alpha = 60\ degree.$ d) The schematic of a geometric effect for uphill fire propagtoin. e) The comparison between experimental result and the analytical model of the geometrical effect.

As illustrated, we observe the fire-front speed increases as we raises the inclination angle. Additionally, as we start to incline the surface, fire starts to propagate at even non-propagating spacing $d = 1cm$ for flat surface, indicating the uphill fire propagation requires less dense forest, and spreads in a faster rate. We also plot the fire propagation phenomenon in terms of the average time the fire stays at each match before the ignition of next match in Fig. 5c. This quantity will become vital in the geometric effect we are about to talk about.

As there is a critical spacing for fire propagation on flat surface, we seek a critical angle for fire to propagate, given a fixed spacing. However, we shortly discover the concept of critical angle may be very complicated due to a geometric effect that propagates fire uphill at large spacing and large inclination. The schematic of this geometric effect is illustrated in Fig. 6d.

Imagine the spacing of two adjacent matches on a inclined surface is sufficiently far, $d > d^*$, so neither the "fast" nor "slow" propagation occurs, yet the vertical projection of the one match falls on another match, $d < L \tan \alpha$, where $L$ is the length of a match in the air. Therefore, when the fire burns down one match, there will be a moment the flame aligns vertically with the head of next match, and the may thus ignite the next match. This phenomenon is described by Fig. 6a-c, where the fire on the 2nd from bottom match does not ignite its neighbor immediately, but rather waits till the flame burns right under its neighbor. Such geometric effect results a constant time delay in propagation, which can be simplified and described in the equation below,

$$\Delta t = \frac{d}{v_0 \tan \alpha} \tag{4}$$

where $v_0$ is the speed of fire burning down a single match. This quantity is weakly dependent on inclination angle, so here we treat it as a constant.

As depicted in Fig. 6e, we compare this analytical model of geometric effect to the experimental results in Fig. 5c. We find a large deviation at small inclination angle, which is expected because at small angle, our assumption $d < L \tan \alpha$ is violated. At higher angle, specifically $\alpha > 40$ degrees, we find the analytical prediction and experimental result agrees in the same magnitude. Noteworthy, this analytical model treats the flame as a semi-infinite vertical line with zero width, and thus we expect nothing but a qualitative match on the trend and magnitudes with the experimental results. Further, this geometric effect only applies to uphill fire propagation.

Generally, the trees on inclined terrain in nature may not grow in the direction perpendicular to the terrain. We use perpendicular matches to simulate the fire propagation only for the simplicity of match positioning and spacing in the experiment. However, our results still provide some important insights, e.g. upslope fire propagation is faster than on flat terrain, which qualitatively agrees with observation of wildfire spread in nature. Additionally, the geometric effect we discover can be a vital factor in small scale fire in extreme elevation environment, where very few literature has investigated.

## 5. Concluding Remarks

In this work, we investigate the fire-front propagation in discrete match array systems, and conduct parameter study on spacing and inclination angle. We find the critical spacing of matches for fire to propagate on flat surface between $8mm$ and $10mm$, and discover two types of propagation with distinct features. Within the critical spacing of “fast” propagation, we find the fire propagating speed is positive relative to spacing, while uncertainty of propagation increase when the spacing of matches is larger than the threshold value. On inclined surface, we observe the fire propagates faster at higher inclination angle. Additionally, we document a geometric effect that facilitates the uphill fire spread, and introduces a constant time delay in the propagation. The analytical capturing this effect agrees qualitatively with the experimental results.

Overall, we believe this work provides quantitative measure on the effects of spacing and inclination angle change, and documents a number of phenomenon/possible mechanism which are vital to understand, model and prevent small scale fire, yet very little studied in the literature. As an exploration work, the experiment is conducted at a relatively low resolution while the theory and understanding remains rather qualitative. The future work in this field is expected to operate at a higher resolution and to conduct more quantitative analysis on 1D and 2D systems, such that analytical/numerical models shall have a better agreement with wildfire spreading in nature.

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