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The interaction between fuel inclination and horizontal wind: experimental study using thin wire

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Abstract: Forward flame spread behavior changes significantly with both the fuel inclination and the wind velocity, but interactions between the inclination and wind is still not well understood. In this work, a controlled laboratory experiment is conducted in a wind tunnel providing a horizontal wind ranged from 0 (quiescent) to 2.5 m/s, and a thin electrical wire as fuel that can be inclined from a horizontal (0°) to a vertical (90°). An electrical wire of 0.8-mm diameter with copper core and polyethylene insulation was used as the characteristic thin fuel. The flame-spread rate, as well as the flame geometrical characteristics, were quantified as a function of the wind velocity and wire inclination. Results show that as the horizontal wind velocity is increased, the flame-spread rate over the wire for all inclination angles first increased to a maximum, and then, slightly decreased until blow-off. The critical inclination for flame acceleration decreases from 45° to 15° as the wind velocity increases. The fastest flame spread along the inclined wire occurs when the wind pushes the flame parallel to the fuel. The interaction between the fuel inclination and wind velocity are quantified using the Froude number. Moreover, the blown-off wind velocity decreases as the fuel inclination is increased, which can be explained by a critical strain rate (536 s^{-1}). This work provides valuable information for fire behaviors under wind not only on the inclined wires and roofs in structure fires, but also on inclined branches in wildland fires.

Keywords: *Flame spread; Cylindrical fuel; Critical inclination; Blow off*

1. Introduction

The spread of flames over the surface of solid combustible material is a complex process involving the interaction between the solid phase (heat transfer, thermal decomposition, gasification) and the gas phase (transport, mixing, chemical kinetics) [1,2]. Experiments on flame spread are often used to determine the fire hazard of a material and the corresponding fire-extinguishing strategy [3]. The flame spread behaviors can change significantly with the fuel characteristics, such as the thickness, inclination, and chemistry, and the environmental conditions, such as airflow, pressure, and gravity level [2]. In general, the flame spread under a forward (or concurrent) gas flow is faster than that under the opposed airflow, representing the worst-case fire scenario.

Several studies have focused on the flame spread in a concurrent gas flow, and most experiments were conducted with thin fuels in a horizontal wind tunnel. For the thick fuel, it is difficult for flame spread to reach steady state in the small-scale experiment. Loh and Fernandez-Pello [4,5] found that the forward flame spread over both horizontally placed thin paper and thick PMMA sheets increased linearly with the horizontal airflow velocity.

Korobeinichev *et al.* [6] found that the forward flame spread over a pine-needle bed can suddenly accelerate, if the horizontal wind velocity exceeded 0.15 m/s. When the sample is vertically placed and ignitited at the bottom, the uprising buoyancy flow can also create a concurrent airflow, i.e., upward flame spread. Markstein and de Ris [7] showed that flame spread over a thin textile may eventually reach steady state under the upward buoyant flow if the length of the sample was large enough. Johnston *et al.* [8] found that the self-induced buoyant flow could be strong enough to blow off the flame in a thin paper. Note that as long as the gravity exists, the buoyant uprising flow will always affect the forward flame spread under a concurrent horizontal flow. Thus, a forward flame spread without the buoyant effect can only be achieved in the microgravity space environment, such as the recent Saffire experiments in the Cygnus spacecraft [9].

If the fuel is inclined, the buoyancy will have a more complex effect on the forward flame spread. Gollner *et al*. [10] found that when the flame was above the flat PMMA sample, the upward flame spread became slower as the fuel was more inclined from the vertical direction. While if the flame was below the sample like a ceiling fire, the slowdown of flame spread did not occur until the inclination was more than 45°. It has also been observed that flame spread can quickly accelerate when the fuel is inclined above 20~25° from the horizontal direction, such as observed for thin paper [11], PMMA [12], and a pine needle bed [13]. Previous experiments using inclined thin wires [14–16] showed that the inclination not only changed the flame-spread rate, but also the extinction limit. Compared to a flat fuel, the upward flame spread over the cylindrical fuel like a wire is simpler, because there is no ceiling fire configuration.

To authors' best knowledge, no study has investigated the flame-spread behavior on an inclined fuel under a horizontal airflow. This study aims to provide a better understanding of the flame spread under the interaction between an uprising buoyancy change due to fuel inclination and a forced horizontal wind. Such interaction is particularly important when the fire is attached to an inclined roof, wires, and tree branches under wind.

2. Experimental method

Experiments were carried out in a 72-m long wind tunnel [17,18], which has a cross-section of 1.5 m wide and 1.3 m high. The horizontal wind was generated by a mechanical fan installed at one end and passed through a honeycomb installed near to the fan to produce a reasonably uniform flow at the test section (uniformity > 95%). A four-probe anemometer was used to monitor the wind velocity which was up to about 2.5 m/s.

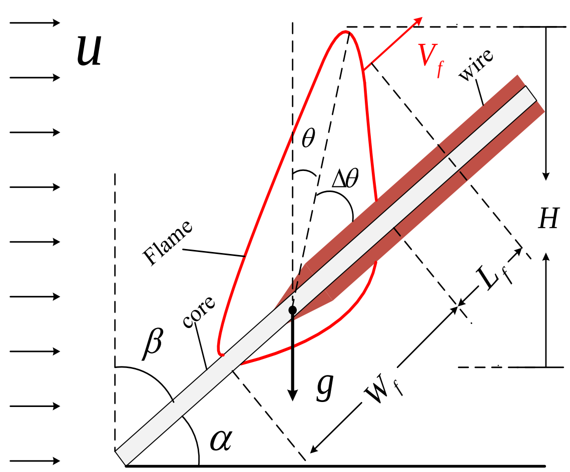

Fig. 1. Diagram of the experimental setup for the inclined thin wire under a horizontal wind.

The experimental apparatus for studying flame spread behavior over the electrical wire was positioned inside the tunnel, as illustrated schematically in Fig. 1. The experimental apparatus, as well as the wire sample, can be adjusted to various inclination (α) ranged from 0° (horizontal) to 90° (vertical), relative to the horizontal wind.

Thin electrical wires of 0.8-mm diameter with high-thermal-conductivity copper core and polyethylene insulation were selected as the fuel. The inner core diameter (d_c) was 0.50 mm, and the insulation thickness (δ_p) was 0.15 mm, same as past studies [19–22]. Compared to the flat fuel, the upward flame spread over the cylindrical fuel like the wire is simpler because the configuration of a ceiling fire does not occur [23]. A thin wire is used because it is a typical cylindrical fuel and has a potential fire risk. The electrical wire was ignited by a coil heater (for about 10 s) at the lower end of the wire. The ignition power was cut-off immediately once the flame was sustained. The flame spread process was recorded by a CCD camera (25 fps, resolution of 3,000,000 pixels). The recorded flame image by the camera was calibrated to its real dimension by a ruler. The characteristic parameters of flame shape, as well as the change of flame front position with time, was deduced from the recorded flame images. All the experiments were conducted in normal air of 26℃. Each case was repeated at least three times.

3. Results and discussions

Figure 2(a) shows the typical photos of spreading flames over inclined wires at different inclination angles (α) and wind velocities (U) before blow-off. Videos of flame spread can be found in the supplemental material. The flame-spread rate (FSR, V_f) is defined as the speed of the flame front, which is obtained by tracking its position using an in-house MATLAB code. Figure 3(a) shows the linearity of the motion of flame front and its steady spread. Figure 3(b) shows the flame-spread rate as a function of inclination and wind velocity.

3.1. Flame spread behaviors

For the horizontal wire (α = 0°), as the wind velocity is increased, the flame becomes longer and tilts more toward the wire. However, the flame never becomes parallel to the wire, because of the uprising buoyancy flow induced by the flame. For an inclined wire (0°< α < 90°), at a small wind velocity, the flame is above the wire due to buoyancy, as shown in Fig. 2(b). Increasing the flow velocity, the flame becomes more parallel to the wire (also circled in Fig. 2a). Eventually, the flame can be pushed below the wire, becoming attached to the stagnation flow behind the wire. Most parts of flame below the wire are still yellow and only the bottom part is blue, and the flame only becomes entirely blue near extinction.

Except for the vertical wire (α = 90°), as the horizontal wind velocity is increased, the FSR first quickly increases to a maximum, and then decreases until blown-off (extinction). For the vertical wire, the (upward) flame-spread rate peaks without the forced wind (U = 0), and as expected, it continuously decreases as the wind velocity increases. Therefore, we can define a critical wind velocity (U_α) for inclination α where the flame and wire are parallel to each other. At this position, the flame spread over the wire is fastest, and the length of flame also reaches the maximum, as shown in Fig. 3(b). The value of U_α is found to decrease with the inclination (α).

Figure 3(b) also shows that the value of maximum FSR along the wire first decreases with an inclination angle to a local minimum at α = 30°), and then increases to the overall maximum at the vertical direction. In other words, the fastest flame spread occurs in upward flame spread over the vertical wire (α = 90°) without wind and consequently represents the worst fire scenario. On the other hand, the blow-off wind velocity (U_{ex}) is found to continuously decrease from U = 1.75 m/s to 0.37 m/s, as the inclination angle increases from α = 0° to 90°.

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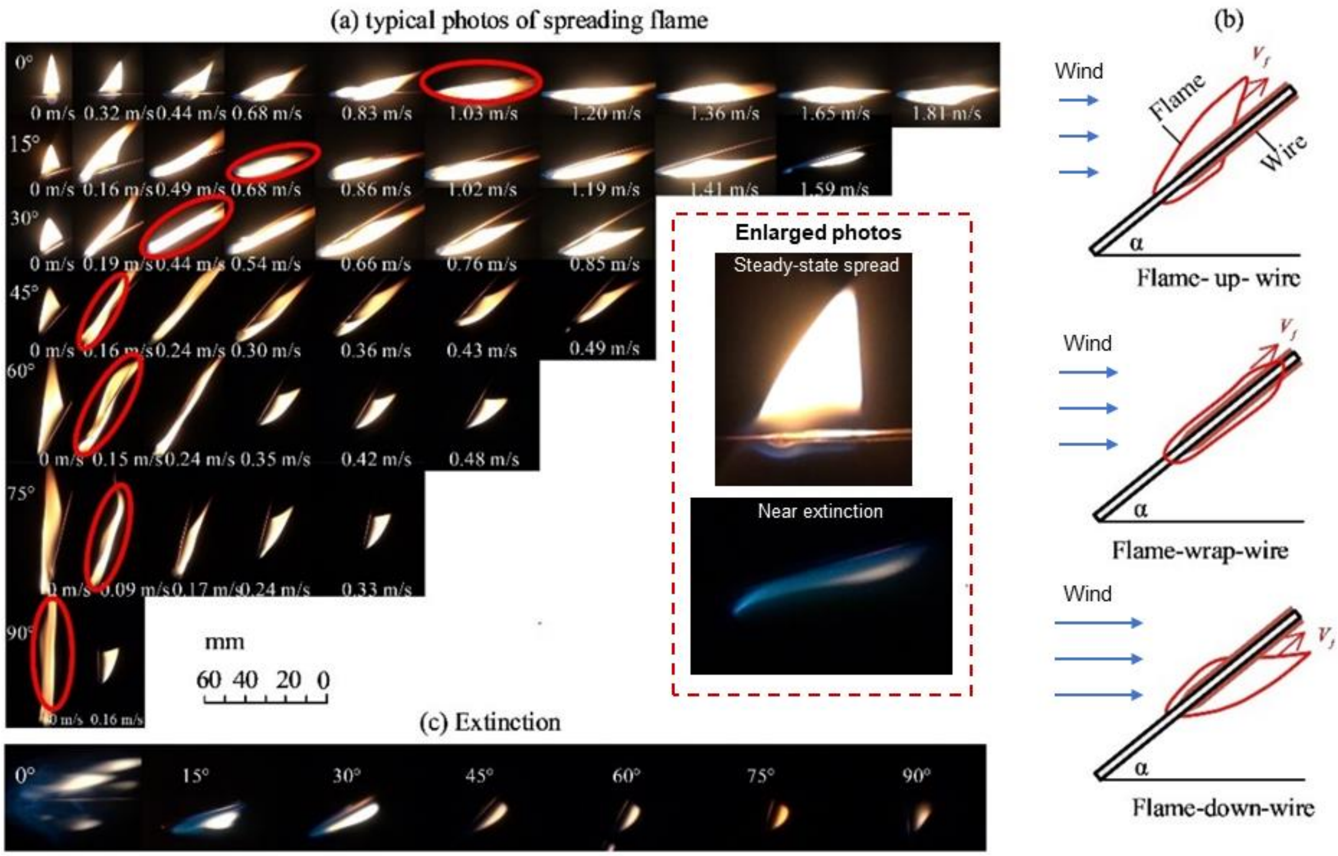

Fig. 1 (a) Typical photos of spreading flames over the electrical wire at different inclinations and horizontal wind velocities, (b) diagram for relative position between flame and wire, and (c) flame extinction behaviors.

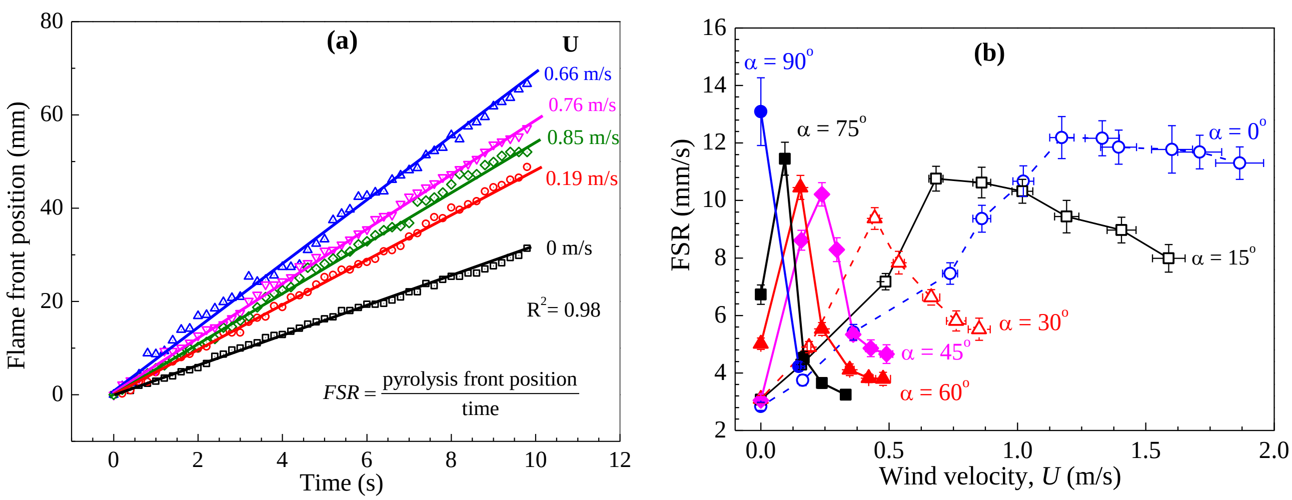

Fig. 3 (a) Flame front position on a horizontal wire changes with time and (b) measured flame-spread rate (FSR, V_f) under varying wind velocity (U) and inclination angle (α).

3.2. The critical inclination for flame acceleration

For the inclined PMMA plate [10,12] and pine needle bed [13], there is a critical inclination, above which flame spread will accelerate. This critical inclination angle was found to be about 15° without wind. However, this measured critical inclination is questionable, because in a real fire there is always some environmental wind.

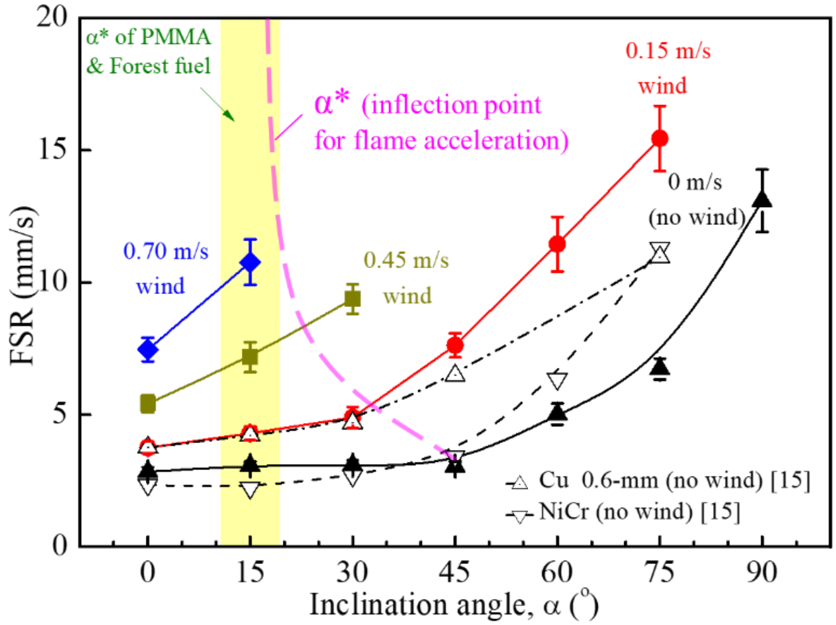

Fig. 4 Flame-spread rate *vs.* wire inclination angle, where the critical inclination angle indicates the rapid acceleration in the flame spread.

Figure 4 shows the increase of the flame-spread rate with the wire inclination under different wind velocities. As the wire is inclined to a critical value (α^*), the flame spread suddenly accelerates, as indicated by the inflection point of the curve. For this thin wire, the critical inclination angle (α_0^*) without wind ($U = 0$) is found to be about 45°, which is much larger than those observed for flat fuels. Such large critical inclination angle was also observed previously for other thin wires [15]. Nevertheless, as the wind velocity is increased, this critical angle will decrease, and eventually disappear at $\alpha \approx 15^\circ$ and $U = 0.45$ m/s. This result lets us to rethink about the definition of the critical inclination angle, which will change with the shape of fuel and the environmental wind.

3.3. Critical wind velocity for the fastest flame spread

The observed variation of the flame-spread rate with the horizontal wind velocity may be explained by the change in the heating from the flame and the core to the preheat zone. Figure 2(a) shows that increasing the horizontal wind velocity, the flame becomes longer and tilts towards the wire. Also, the width of the burning region (W_f) becomes larger, as it is quantified in Fig. 5(a-b). The former enhances the convective heat flux from the flame to the preheating region (L_f), and the later raises the temperature of the core. Figure 5(c) shows an empirical correlation between the flame-spread rate and two flame length scales. A good linearity is found, mainly because these two flame length scales include the implicit information about flame shape and inclination (also see the scale analysis in [24]). Thus, for a first approximation, the flame-spread rate could be estimated based on the flame geometric characteristics.

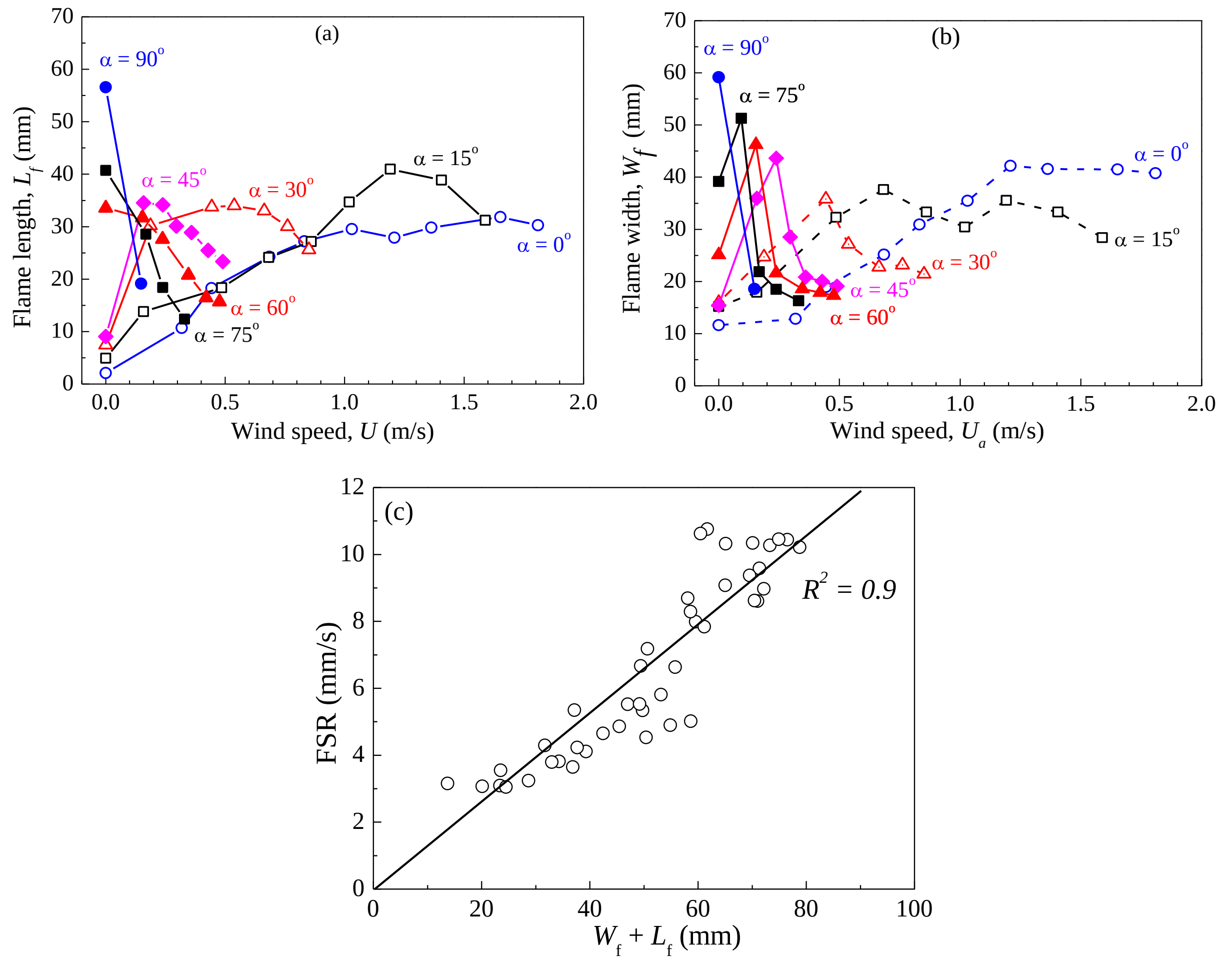

Fig. 5 (a) Length of the preheating region (L_f), (b) width of the flame base (W_f), and (c) the empirical correlation between FSR and $L_f + W_f$

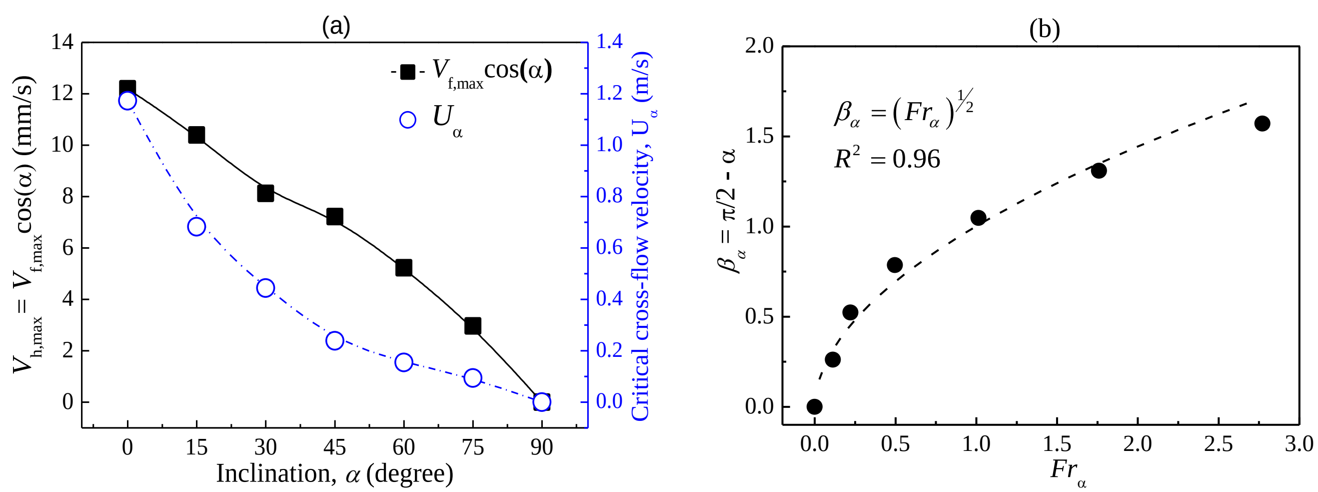

Fig. 6 (a) The maximum horizontal FSR ($V_{h,max}$), and critical wind velocity (U_α) under different inclinations, and (b) correlation between the inclination and Froude number (Fr_α).

The maximum flame-spread rate along the inclined wire ($V_{f,max}$) is reached when the flame can be pushed parallel to the wire (i.e., $\theta = \beta = \alpha$ in Fig. 1), under the critical wind velocity (U_α). Figure 6(a) compares this critical wind velocity with the maximum horizontal flame spread ($V_{h,max} = V_{f,max} \cos\alpha$) under different inclinations. As expected, both the maximum horizontal flame spread and the critical wind velocity decrease with the inclination, but in a different rate of decrease, as the wind primarily drives the flame spread in the same direction. Thus, the combined effect of buoyancy and inclination determine the flame spread rate.,.

To describe the interaction between the uprising buoyancy flow and horizontal wind, a Froude number could be defined as

$$Fr = \frac{U}{\sqrt{gH_0}} \tag{1a}$$

where H_0 is the flame height without any horizontal wind (see the definition of flame height in Fig. 1). Thus, there is a critical Froude number at the critical wind velocity (U_α)

$$Fr_\alpha = \frac{U_\alpha}{\sqrt{gH_0}} \tag{1b}$$

which can be correlated to the wire inclination ($\beta_\alpha = \pi/2 - \alpha$) via a power law, $\beta_\alpha = Fr_\alpha^{\frac{1}{2}}$, as fitted in Fig. 6(b).

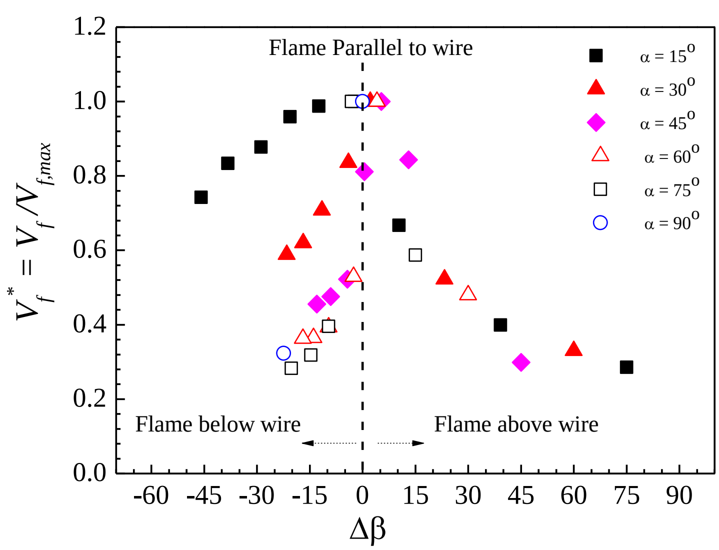

Fig. 7 Normalization flame-spread rate vs. Δβ

At the same time, the inclination of flame with respect to the wire can be redefined as

$$\Delta\beta = Fr_\alpha^{\frac{1}{2}} - Fr^{\frac{1}{2}} = \left(\frac{U_\alpha}{\sqrt{gH_0}}\right)^{\frac{1}{2}} - \left(\frac{U}{\sqrt{gH_0}}\right)^{\frac{1}{2}} \tag{2}$$

Figure 7 shows the correlation between the normalized flame-spread rate ($V_f^* = V_f / V_{f,max}$) and $\Delta\beta$ where $\Delta\beta > 0$ for flame above the wire, and $\Delta\beta < 0$ for flame below the wire. Such correlation can successfully remap all the data (except for horizontal wire) in Fig. 3 (b) into the new coordinates ($\Delta\beta$) including the combined buoyancy-flow and forced-wind effect.

3.4. Blow-off under inclination

At a large wind velocity, the flame is pushed to the downstream side and beneath the wire (except for the horizontal wire), and eventually is blown off. Near blow off, the flame can still envelope the entire wire, and its upstream part becomes blue. Wake flame is not observed, probably because the wire diameter and the wake region behind are too small. Figure 8(a) shows the correlation between blow-off flow velocity and the wire inclination. The flame blow-off may be explained by a critical Damköhler number, when the chemical time scale becomes long, compared to the flow time scale. Thus, we can define a global strain rate (a) around a cylinder [25] to represent the flow time scale as

$$a = \frac{U_O + U_F}{R} \approx \frac{U_O \sin\alpha}{R} \tag{3}$$

where the fuel velocity is much smaller than the airflow velocity $U_F << U_O$, $U_O \sin\alpha$ is the wind velocity perpendicular to the wire, and R is the characteristic radius of wire near extinction as

$$R = \begin{cases} r_o & \left(0^o < \alpha < 90^o\right) \\ r_c & \left(\alpha = 90^o\right) \end{cases} \tag{4}$$

In the vertical direction (α = 90°), the blow-off occurs when the most insulation polyethylene burns out. In other words, the core is exposed to the flame directly, so the radius of the core is selected as the characteristic radius, $R = r_c = 5/8 r_o$.

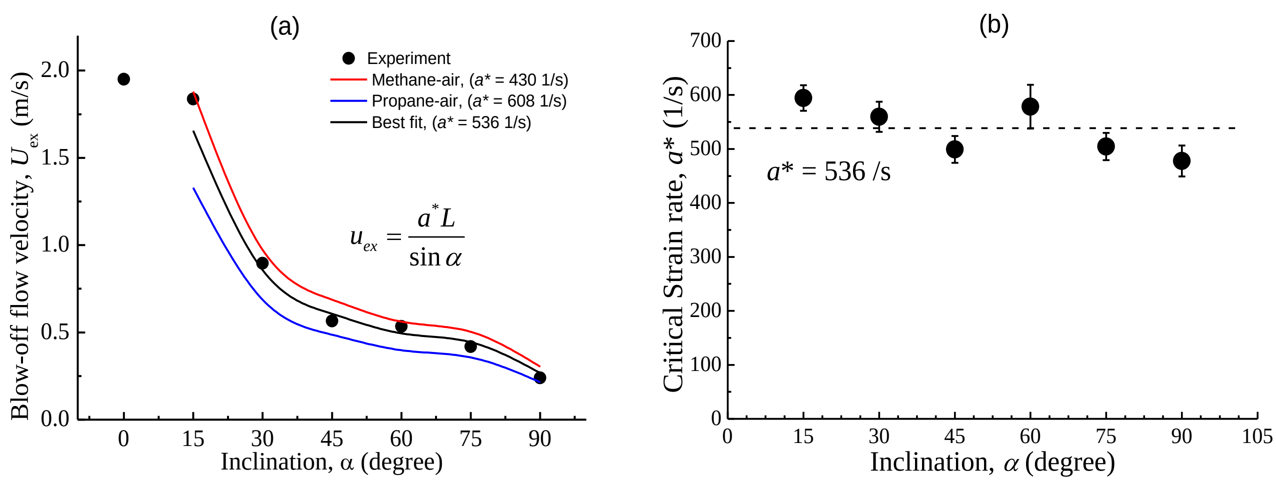

Fig. 8 (a) Blow-off flow velocity (U_{ex}), and (b) calculated critical strain rate (a*) as a function of inclination (α).

Therefore, the critical strain rate (a*) can be calculated at the moment of blow-off, as shown in Fig. 8(b). In general, the values of critical strain rate are similar, ranging from 500 to 600 s-1, and have an average value of 536 s-1. This value is also close to those found in the cylindrical counter-flow flame (430 s-1 for methane flame and 608 s-1 propane flame) [25]. Using this critical strain rate and Fig. 8(a), the blow-off wind velocity under other inclination angles may also be predicted. Future experiments are needed to determine whether this critical strain rate can be applied for cylindrical fuel of a larger diameter and different material.

4. Conclusion

In this work, we conducted a new controlled laboratory experiment in a wind tunnel providing a horizontal wind up to 2.5 m/s, and with a thin electrical wire inclined from horizontal (0°) to vertical (90°). A thin electrical wire of 0.8-mm diameter with copper core and polyethylene insulation was used in the experiments. Unlike using a flat fuel, neither the flame or airflow are blocked by the cylindrical fuel, which makes the fire phenomenon unique and the analysis simple.

Experimental results show that as the horizontal wind velocity is increased, the flow assisted flame-spread rate over the wire for all inclinations first increased to a maximum, and then, slightly decreased until blow-off occurs. The fastest flame spread along the inclined wire occurs when the wind pushes the flame parallel to the fuel. The critical inclination for flame acceleration decreases from 45° to 15°, as the wind velocity is increased. The interaction between the fuel inclination and wind velocity are quantified using a Froude number that includes the flow velocity and the flame length. Moreover, the blown-off wind velocity decreases as the fuel inclination is increased, which can be explained by a critical strain rate (536 s^{-1}) that includes the inclination angle. This work provides valuable information for fire behaviors under wind not only for inclined wires and roofs in structure fires, but also for inclined branches in wildland fires.

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