Comparative study on upward flame spread over single and twin polyethylene-insulated copper core wires at different inclination angles

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Abstract:

In this paper, a series of comparative experiments were performed to study the upward flame spread over single and adjacent twin polyethylene-insulated copper wires from horizontal (0°) to vertical (90°). The flame morphology and flame spreading rate of single and twin wires were compared at different inclination angles, which show a larger flame size, but a lower overall flame spread rate over twin wires. As the inclination angle increases, the flame characteristic length, and flame spread rate increase with the inclination angle for both wire arrangements. The flame spreads steadily to the end of the sample without molten dripping or sliding for single-wire conditions. However, molten dripping or sliding behaviors were found during flame spreading for twin-wire conditions, and the averaged dripping or sliding frequency increases with the inclination angle. Correspondingly, the periodical variation of flame characteristic length, flame height, and flame spread rate for twin-wire conditions have been investigated in detail compared with single-wire conditions. Finally, a simplified heat transfer analysis is carried out to quantitatively study the flame spread rate for both wire arrangements, and the effects of molten dripping/sliding and overlapped area on the heat transfer and flame spread rate are qualitatively discussed.

Keywords:

Wire fire; Twin wires; Upward flame spread; Inclination angle; Molten dripping

1.Introduction

Electric wires are widely used in industrial production and daily life, as well as in aerospace. The combustible insulation materials of electrical wire can be ignited by unexpected arcing, short-circuiting, and overheating, which presents a substantial risk of fire outbreak [1]. Once the electrical wire fire occurs, the fire can propagate quickly along the electrical wire to ignite other combustibles, and consequently release a large amount of heat and toxic smoke, which may pose a great threat to people's lives and property. In China, a total of more than 85 000 electrical fires occurred in 2020, which accounted for 33.6 percent of the total number of fires [2]. In the United States, about 25 900 residential building electrical fires were reported annually from 2009 to 2011, resulting in an estimated 280 deaths, 1 125 injuries, and $1.1 billion in property losses [3].

Due to the special role of the wire core with high thermal conductivity, the flammability and fire behaviors of electrical wire are different from that of typical insulation materials [2]. The ignition and flame behaviors along electrical wires have become a key issue in fire safety, which has been investigated extensively in recent years [2, 4-18]. Fujita and Nakamura et al. mainly studied the flame behaviors over electrical wires under microgravity conditions and proposed that the existence of metal core played two important roles of heat source and heat sink on flame spread characteristics [4, 6, 16]. They also experimentally observed the effects of core diameter, ambient oxygen concentration [19, 20], external flow [4, 21], sub-atmospheric [4, 5], etc. on flame spread characteristics over electrical wires. Besides, Kim [7], Lim [10, 22], and Park [1, 23, 24] investigated the influences of alternating and direct current electric fields on flame spread along electrical wires. Recently, Hu and Zhang et al. performed a series of experiments to study the influences of both internal and external parameters on flame-spreading behaviors over polyethylene (PE)-insulated electrical wires, such as insulation thicknesses [13, 25], core diameter [11, 12, 25], pressure [14, 26, 27], air flow [13, 15, 25]. In addition, Huang [8], Wang [28-30], and Zhang [2] investigated ignition behaviors and the heat transfer mechanism of flame spread for electrical wires.

Besides the previous work mainly focused on downward or horizontal spread behaviors over electrical wires, the inclination angle affects the upward flame spread significantly by changing the direction of the gravity as well as the buoyant flow. In recent years, Hu et al. [9] revealed the flame spreading over electric wires with different sample inclination angles ranging from -90° (downward) to +90° (upward), and reported that the flame spread rate first decreased, reaching a minimum at the nearly horizontal condition, and then increased with inclination angle. Moreover, the limiting oxygen concentration for the extinction of upward flame spreading over nichrome (NiCr) wires at varying inclination angles has also been investigated [31]. A series of experiments by Lu et al. [15] observed the interaction effects between sample inclination and horizontal wind on flame spreading over electrical wires, which found that as the horizontal wind increased, the critical inclination angle for flame acceleration decreased from 90° to 15°. Nevertheless, the inclination angle effects on upward flame spread over polymethyl methacrylate (PMMA) [32-34], polyurethane foam (PU) [35-37], wood [38], fabric fuels [39, 40], etc have been commonly observed. Owing to the existence of the metal core, the flame spread behaviors and heat transfer mechanism over inclined electrical wires differ from that of plate materials. Most fundamental studies focus on the flame spread behaviors over a single electrical wire to establish the theoretical model. However, most electrical wiring involves pairs of wires in actual conditions [1], study on flame spreading over twin wires could provide more insights into the flame spread of wire harnesses. Citerne et al. [41] firstly studied the fire spread behaviors under the interaction of parallel multi-wires in a microgravity environment. Park et al. [1] investigated the fire spread behaviors over horizontal twin electrical wires taking the effects of varying voltages and wire gap into account. Besides, the flame spread characteristics of double horizontal PE-insulated wires with varying spacing have been experimentally observed by Huang et al. [42] and Lu et al. [43]. Whereas, the studies mentioned above have been concerned with horizontal spread of twin wires, although the flame spread over inclined fuels is a common fire-hazard scenario.

As the fundamental studies always used the non-charring polymer insulation for the wires, the molten dripping behaviors are important for the propagation of a fire because the burning molten material can ignite the other combustibles and may affect the flame spread characteristics. Bakhman et al. [44] first investigated the phenomenon of molten dripping and sliding of electric wire fire, and pointed out that the melting of polymer has an important effect on the burning rate. Since then, the molten dripping or sliding characteristics under horizontal and vertical conditions of single wire fire have been wildly studied under the effects of oxygen concentration [20, 45], pressure [45, 46], external radiation [47], airflow [48], current [2, 10, 12], etc. Moreover, the molten insulation characteristics of electrical wire under microgravity conditions were also studied and analyzed [19, 21, 49]. The inclination angle can also change the behaviors of molten dripping or sliding over a burning electrical wire. Zhang et al. [50] studied the critical conditions of dripping on PE-insulated wires with various pressures, inclination angles and oxygen concentrations, and developed a theoretical model incorporated the balance between insulation consumption and melting rate.

In the present work, to give a better understanding of inclined upward flame spread over single and twin electrical wires, not only the flame but also the molten dripping behaviors were considered. A series of comparative experiments were carried out using single and twin electrical wires with different inclination angles varying from 0° to 90°. To clarify the effects of inclination angle and molten dripping or sliding, some essential parameters were obtained and compared simultaneously, including flame shape, flame characteristic length, flame height, and flame spread rate.

2.Experimental Setup

The experimental setup is schematically illustrated in Figure 1, which is mainly composed of a sample holder, rotary supporter, ignition system, and electrical wire sample. The electrical wire samples are 90.0 cm in length, whose bare ends are installed on the insulation blocks on both sides. One of the insulation blocks is connected to a spring to ensure the electrical wire is straightened and to prevent the electrical wire from bending during fire experiments [9, 10]. The rotary supporter configuration consisted of a screw, protractor, and base support allowing the electrical wire sample orientation at a desired inclination angle to the horizontal. Moreover, a spirit level is fixed on the base support to make sure the accuracy of the inclination angle. A coil heater decorated on the right side of the device is regarded as an external ignition source, which is connected to a DC (Direct Current) source with a voltage range of 0~30 V and a current range of 0~10 A. The coil heater with an outer diameter of 5.0 mm is made of NiCr with a diameter of 1.0 mm, and the length of the heating area is 20.0 mm. Two digital video cameras (Sony FDR AX-60) with a data acquisition frequency of 25 frames per second are set at the front of the electrical wire to record the flame spread process and flame morphology. A K-type thermocouple is installed above the electrical wires to obtain the flame temperature, whose measure range is 0~1200 °C, with a bead diameter of 0.5 mm. In addition, to facilitate the image data analysis, a scale bar is attached to the pole above the electrical wire.

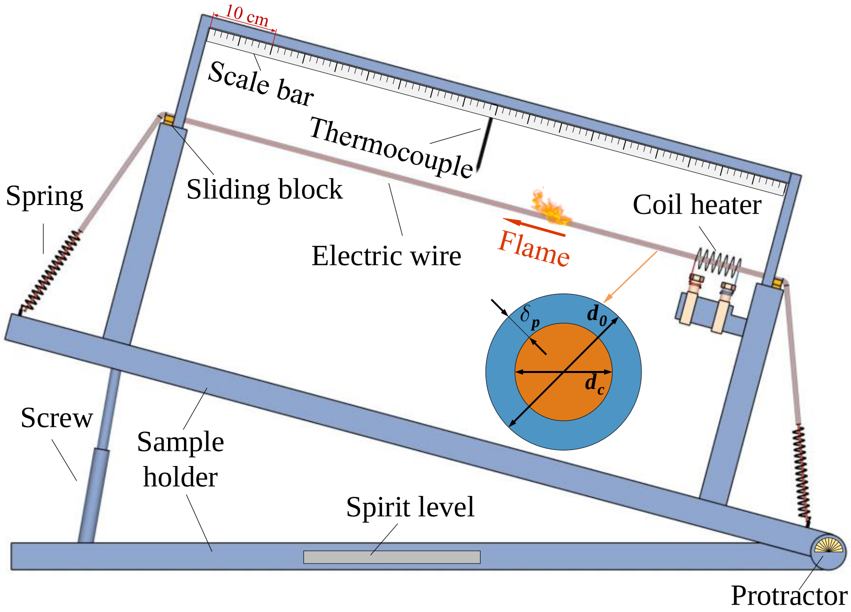


Figure 1 A schematic of the experimental setup.

Table. 1 Physical properties of core and insulation materials [11].

Physical properties	Values	
	PE insulation	Cu core
Density (kg/m^3)	930	8 960
Thermal conductivity (W/m/K)	0.42	400

Specific heat (kJ/kg/K)	1.916	0.39
Pyrolysis temperature (K)	648	--
Flash point (K)	673	--

Table. 2 Configurations of the sample wire.

Core	Insulation	Core diameter (d_c/mm)	Thickness of insulation (δ_p/mm)	Outside diameter (d_0/mm)
Copper	Polyethylene	0.50	0.15	0.80

We selected PE-insulated wires with an inner copper (Cu) core diameter d_c of 0.5 mm and an insulation thickness δ_p of 0.15 mm as the test samples, which are similar to the fuel used in previous work [9, 11]. The configurations and thermal parameters of sample wires are summarized in Table 1 and Table 2. The upward flame spread experiments are performed using single and twin wires, and the twin wires are horizontally placed close together. In previous work by Lu et al. [43], the spring tensioner is applied to tighten the wires straightly and to keep the parallel twin wires arranged at a fixed distance. However, there is still a small gap between the two wires for a very few parts, but its effects on the flame spread are limited from the experimental results. The various sample inclination angles (θ) of 0°, 15°, 30°, 45°, 60°, 75° and 90° are applied in this work. Through pre-ignition tests, the coil heater is applied 150 W to act as the ignition source and energized for about 10 s to ensure the successful ignition of both single and twin wires. To avoid the influence of the end and ignition source, the data within 10.0 cm at both ends of the electrical wires are ignored, thus the effective length of the electrical wires is 70.0 cm in upward flame spread experiments. Besides, the electrical wire samples are marked at intervals of 5.0 cm to clearly determine the position of the flame front. All the experimental conditions are summarized in Table. **3**. To minimize the experimental uncertainty, three repeated experiments are carried out for each test condition in a test hall in still air.

Table. 3 Summary of experiments conditions.

Test No.	Wire number	Arrangement	Sample inclination angle (°)
1-7	Single		0, 15, 30, 45, 60, 75, 90
8-14	Twin		0, 15, 30, 45, 60, 75, 90

3.Results and discussions

3.1 Flame spread behaviors

Figure 2 presents the flame morphology from a side view at different inclination angles in the stable flame propagation stage for single-wire and twin-wire conditions, respectively. Generally, the flame can be divided into two parts, yellow at the upper part and blue at the bottom, whether for single-wire or twin-wire flame spread. Notably, the flame below the electrical wire is significantly smaller than the flame above the electrical wire between 0° to 75°. It can be seen that as the inclination angle increases, the flame volume and flame length increase significantly, especially in the stage of inclination angle increasing from 60° to 90°. Moreover, when the electrical wire is placed horizontally, the flame above the electrical wire is perpendicular to the wire and the tip region is relatively rounded. As the inclination angle increases, the upper flame gradually inclines toward the wire, and the tip region becomes slender and sharpened. Until the wire is arranged vertically, the upper and lower flames are completely wrapped and parallel to the wire. Apparently, the flame below the wire does not change significantly for different inclination angles, except for vertical configurations. Besides, the flame size and shape at the same inclination angle for twin-wire conditions are different from that for single-wire conditions, which will be further analyzed in the following parts.

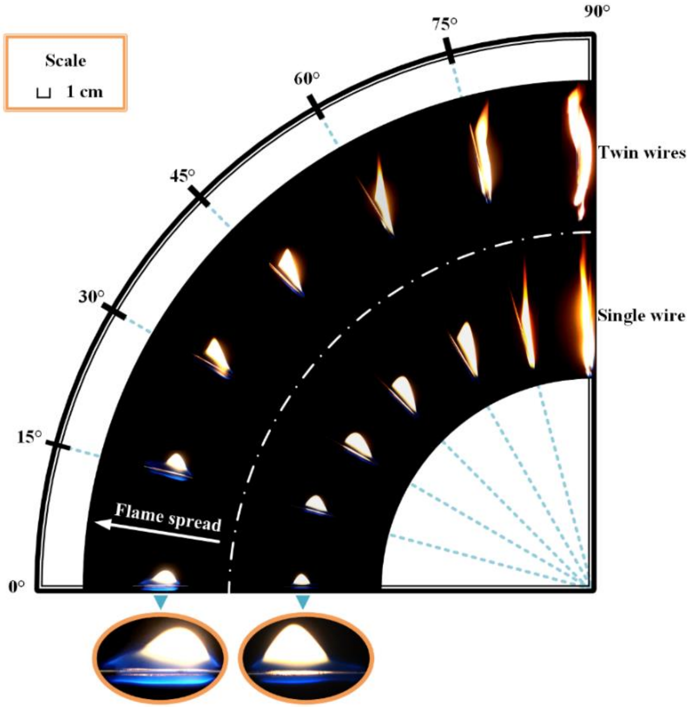
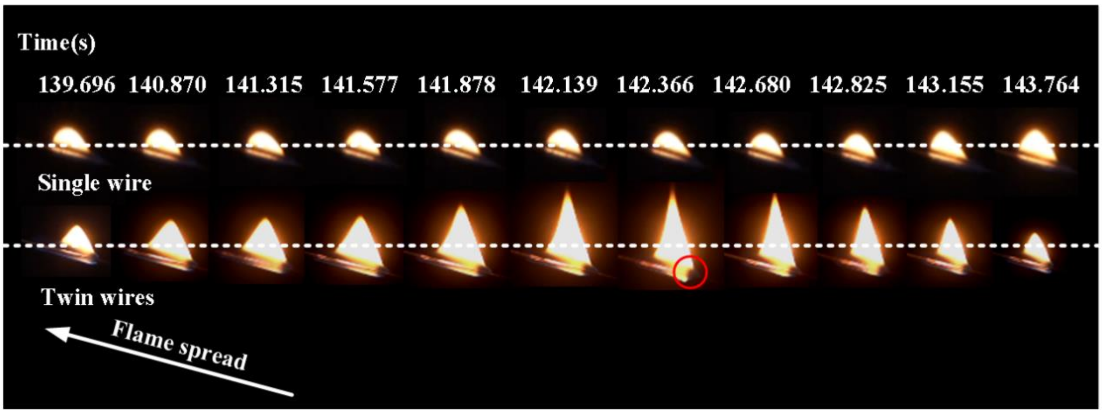


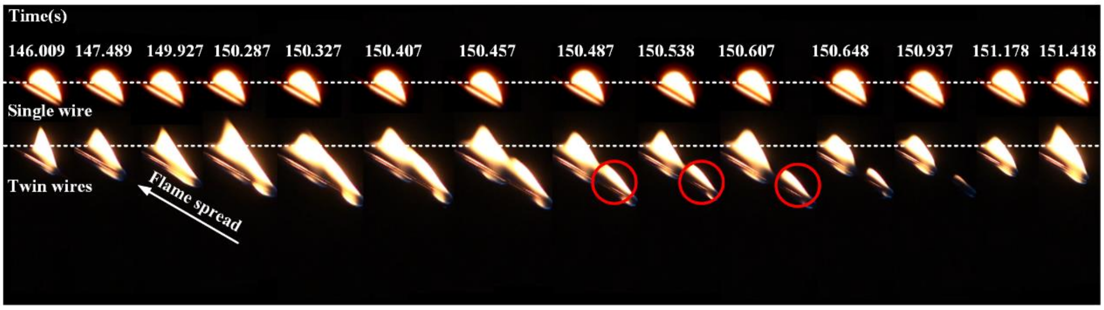
Figure 2 Flame morphology from a side view at different inclination angles.

Figure 3 shows time-sequence images of spreading flames over inclined wires at typical inclination angles for single-wire and twin-wire conditions, respectively. It can be seen that for single-wire conditions, no matter what the inclination angle is, the flame spreads steadily to the end of the sample without molten dripping or sliding. However, the flame-spreading behaviors for twin-wire conditions show a different manner. When the twin wires are arranged horizontally, the molten dripping behavior is observed periodically during flame spreading. As the flame propagates, the molten insulation accumulates below the wire, and then the mass of the molten insulation increases. The molten dripping behavior will occur once the gravity exceeds the surface tension of the molten insulation, and then the flame size will change obviously, and the wire combustion becomes weak, and the flame continue to spread hardly. Huang et al. [42] reported that when the two horizontal wires were arranged closely attached together, the wire combustion was very week and even the flame did not spread. Subsequently, the flame height will self-adjust and gradually return to the initial height, which will form a periodic change. The molten dripping and periodic fluctuation of flame height were also investigated over horizontal electrical wire by previous work [2]. However, when twin wires are inclined, the molten insulation sliding occurs periodically during flame spreading. For 15° inclination angle conditions, the flame will be gradually elongated as the molten sliding accumulates along the wire, and then shortened as the molten sliding is consumed. But as the inclination angle increases beyond 30°, the molten insulation accumulates and will flow downwardly, and consequently the flame is divided into two parts. That is, the upper part continues to spread upward and the lower part gradually decreases until extinguishes due to the depletion of molten insulation. Subsequently, the flame will self-adjust and change periodically.

(a) Single-wire and twin-wire conditions at θ=0°



(b) Single-wire and twin-wire conditions at θ=15°



(c) Single-wire and twin-wire conditions at θ=30°

Figure 3 Time-sequence images of spreading flames over inclined wires for single-wire and twin-wire conditions, (a) θ = 0°, (b) θ = 15°, (c) θ = 30°.

To quantify the effect of inclination angle on dripping and sliding processes, the frequency of dripping or sliding (f_{dr}) is introduced for analysis, which can be expressed as [46]:

$$f_{dr} = \frac{N}{\Delta t} \quad (1)$$

where N is the total number of dripping or sliding in the whole spreading process and Δt is the time interval from the beginning of the flame spread to the end. The variation of frequency (f_{dr}) with inclination angle is shown in Figure 4. It can be seen that when the inclination angle increases from 0° to 60°, frequency (f_{dr}) shows a slightly increasing trend, but as the inclination angle varies from 60° to 90°, the frequency (f_{dr}) increases substantially. The molten dripping occurs when the gravity exceeds its surface tension, while the occurrence of molten sliding is attributed to viscous force and the component of gravity parallel to the wire ($g\sin\theta$), as shown in Figure 4. With the inclination angle rises, the surface tension of molten PE could be more considerable [50], requiring a larger critical dripping diameter. However, due to the heat feedback from the lengthened flame, especially for $\theta > 60°$ conditions, the promoted melting and pyrolysis would accelerate the circulation of dripping and sliding.

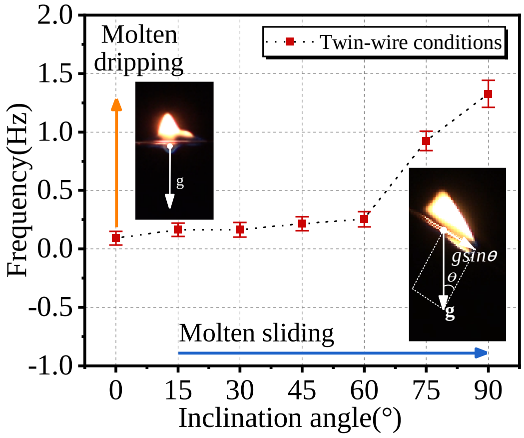
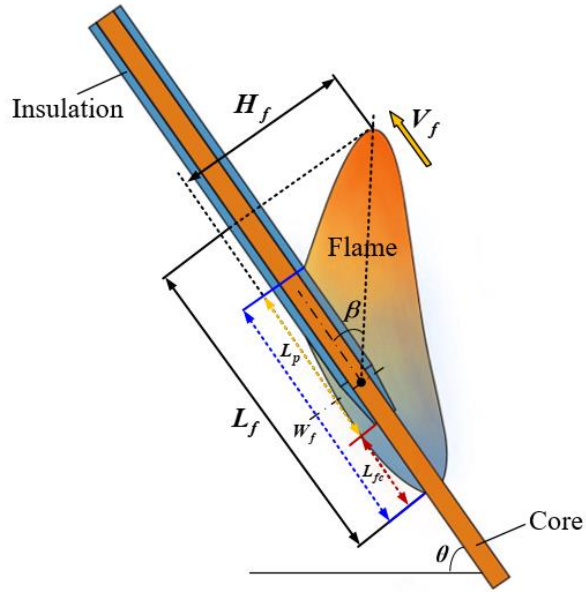


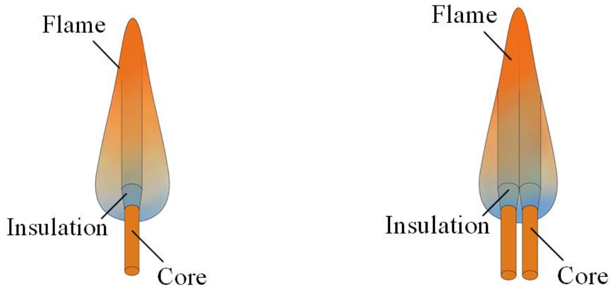
Figure 4 Relationship between frequency and inclination angle of twin-wire conditions.

3.2 Flame characteristics lengths

The schematic flame morphology from both side and front views for upward spreading over inclined single and adjacent twin electrical wires are shown in Figure 5. The flame characteristics lengths have been considered, flame length parallel to the wire and flame height normal to the wire, which can imply the heat feedback from the flame to the wire sample. The flame length (L_f) is defined as the projected distance of the entire flame along the direction of the wire, while the flame height H_f is defined as the distance from the bottom to the tip of the flame in the perpendicular direction of the wire. The length of the electric wire surrounded by the flame W_f includes the length of the bare core wrapped by flame (L_{fc}) and the length of pyrolysis zone part (L_p). The flame tilt angle (β) is the angle between the sample wire and the upper flame centerline, which is the line from the flame tip to the middle of wire surrounded by the flame.



(a) Side view of single-wire and twin-wire

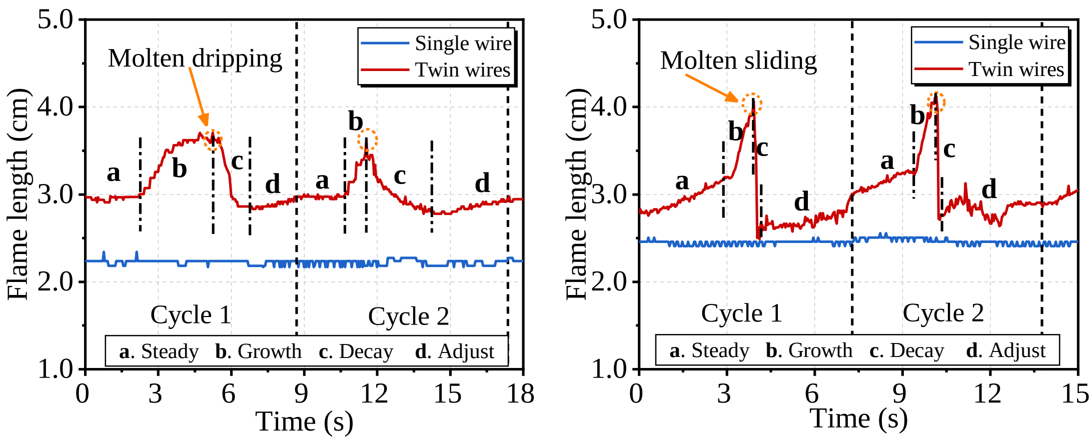


(b) Front view of single-wire (c) Front view of twin-wire

Figure 5 Schematics of flame morphology for spreading over inclined electrical wires, (a) Side view of single-wire and twin-wire, (b) Front view of single-wire, and (c) Front view of twin-wire.

Figure 6 shows examples of time variations of flame length at typical inclination angles (0° and 30°) for single- and twin-wire conditions, differently. Apparently, the flame length is stable and fluctuates around a fixed value for single-wire conditions, and the flame will fluctuate more significantly as the increase of inclination angle. However, the flame length goes through different stages in one cycle for twin-wire conditions due to the molten dripping or sliding. The variations of flame length for twin-wire conditions in one cycle can be divided into four stages, including steady, growth, decay, and adjusting stages. Before molten dripping ($\theta = 0°$), the flame length increases as the flame propagates. When molten dripping occurs, the flame length decreases sharply. Subsequently, due to the energy balance of flame spreading, the flame length will self-adjust and then gradually return to the steady stage. Notably, the steady stage is relatively short due to the fast-sliding frequency when molten sliding ($\theta > 0°$) occurs. This periodic fluctuations of flame length is due to the molten dripping and sliding, which is basically similar to the previous work by Zhang et al. [2]. As the burning progresses, more fuel is burned, and more heat is generated and feedback to the wire insulation. This positive heat feedback leads to the accelerations of both the melting rate and burning rate, resulting in the growth of flame length. Since the melting rate of insulation is faster than the consumption rate, the molten insulation accumulates until molten dripping or sliding occurs when gravity exceeds the surface tension [50]. As a large amount of heat are taken away by the molten dripping or sliding, the flame length decreases suddenly. Then, due to the energy balance in the process of flame propagation, the flame length will self-adjust and gradually increase [2]. Compared with the conditions with molten sliding, the flame length with molten dripping decreases more rapidly in the decay stage.

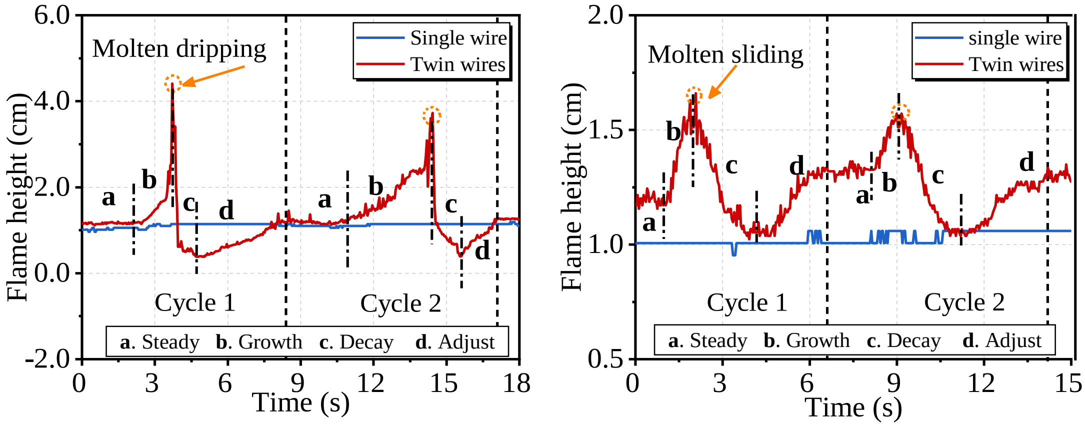
Similarly, examples of the time variation of flame height at typical inclination angles for single- and twin-wire conditions are shown in Figure 7. The flame height changes around a fixed value for single-wire conditions, while the flame height varies periodically with time and goes through different stages in one cycle for twin-wire conditions.



(a) $\theta = 0°$ (b) $\theta = 30°$

Figure 6 Time variations of flame length at different inclination angles, (a) $\theta = 0°$, (b)

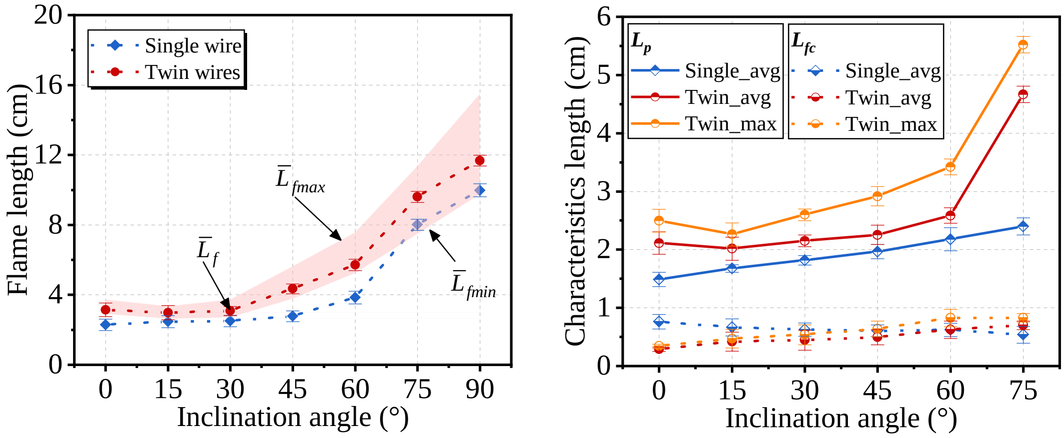
θ = 30°.



(a) θ = 0° (b) θ = 30°

Figure 7 Time variations of flame height at different inclination angles, (a) θ = 0°, (b) θ = 30°.

Moreover, the mean values of flame length ($\bar{L}_f$) in the steady stage with inclination angle for single-wire and twin-wire conditions are plotted in Figure 8 (a), as well as the average values of the maximum flame length ($\bar{L}_{fmax}$) and minimum flame length ($\bar{L}_{fmin}$) during the molten dripping and sliding for twin-wire conditions. The maximum value is the flame length when the molten dripping or sliding occurs in one cycle, and the minimum value is the minimum flame length after the molten dripping or sliding occurs. It's worth noting that for single-wire and twin-wire conditions, the flame length gradually increases as the inclination angle increases from 0° to 45°, whereas it rises sharply as the inclination angle is beyond 60°. Additionally, except for an inclination angle of 0°, the corresponding flame length for twin-wire conditions is larger than that for single-wire conditions. Furthermore, when the inclination angle changes from 0° to 15°, the difference between the maximum and minimum flame length decreases, which is caused by the different mechanisms of molten dripping and sliding. The subtraction of maximum and minimum flame length increases with inclination increases from 30° to 90°, which demonstrates that the effects of molten sliding on flame length become more obvious. Besides, L_{fc} and L_p are directly related to the heat transfer process in the following Section 3.3, as summarized in Figure 8 (b). In the legends of Figure 8 (b), "avg" corresponds to the averaged value in the steady stage, and "max" corresponds to the maximum values in the acceleration stage as defined in Figure 6. We can find that L_{fc} is much smaller than L_p at different inclination angles and the changes of L_p with inclination angle are more obvious than that of L_{fc}.



(a) Flame length (L_f) (b) Lengths of L_{fc} and L_p

Figure 8 Variations of L_f , L_{fc} and L_p at different inclination angles.

Figure 9 shows the variations of the average flame height ($\overline{H}_f$) in the steady stage for single-wire and twin-wire conditions, respectively. Apparently, $\overline{H}_f$ increases overall with inclination angle, except for 90°, because the flame is parallel to the wire for vertical configuration. When the wire is placed horizontally, the flame "liftoff" from the sample surface by vertical buoyant acceleration. As the inclination angle increases, the flame height is determined by the component of buoyant acceleration perpendicular to the sample surface. For the vertical configuration, the direction of buoyant acceleration and the flame are parallel to the wire. But the flame size increases with inclination angle, which can be seen from Figure 3. Thus, the variations of $\overline{H}_f$ with inclination angle are determined by the flame size and the change of buoyant acceleration direction, in which $\overline{H}_f$ shows a small decrease at 90° inclination angle. The drop in flame height at 90° inclination angle was also observed in upward flame spread for polymethyl methacrylate (PMMA) [51] and cotton fabric [52].

The corresponding values of H_f for twin-wire conditions are larger than that for single-wire conditions. The results show that the larger flame height in twin-wire conditions gives a larger distance that the flame heat flux action on the preheating region by conductive heat transfer. Besides, for twin-wire conditions, the differences between the maximum flame height ($\overline{H}_{fmax}$) when the molten dripping or sliding occurs and the minimum flame height ($\overline{H}_{fmin}$) after the molten dripping or sliding occurs become more obvious with inclination angle, except for 0° and 15° inclination angle. For horizontal configurations, when the molten dripping occurs, a large amount of heat is taken away by the droplet and consequently the flame height decreases suddenly, resulting in a large difference between $\overline{H}_{fmax}$ and $\overline{H}_{fmin}$. This large difference in flame height was also observed for horizontal single wire in previous work by Zhang et al. [2]. When the inclination angle is 15°, the molten sliding behavior begins to be observed. As the inclination angle increases further, the molten sliding and flame fluctuations become relatively more obvious. This observation demonstrates the effects of molten dripping and sliding on flame spread process.

According to the above measurements of flame characteristics lengths for single- and twin-wire conditions, both averaged lengths and thicknesses in twin-wire flame spread are larger than that of single-wire cases, which implies the longer preheating zone but a larger thickness for conductive heat feedback from the flame to the wire sample. Therefore, the flame tilt angle (*β*) is the angle between unburned wire and the flame sheet [39, 40], which can reflect the difference of flame heat feedback intensity between the single and twin wires more intuitively, as plotted in Figure 10. As can be seen in the figure, the flame tilt angle is slightly higher in twin-wire conditions, which implies that the averaged heat feedback intensity is slightly lower than that in single wire conditions. More insights can be found from the discussion on flame spread rate in the next section.

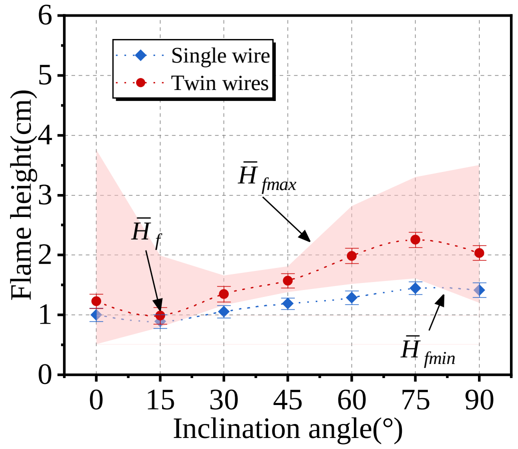


Figure 9 Variations of flame height at different inclination angles.

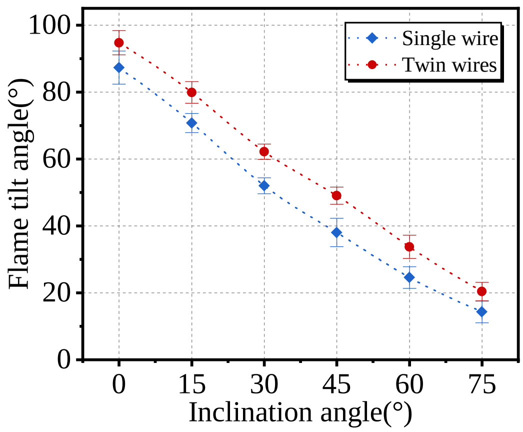
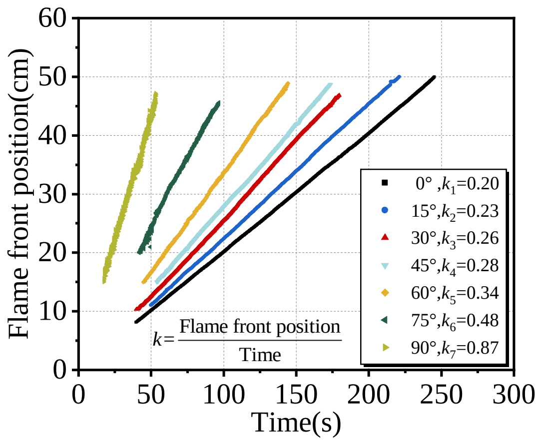


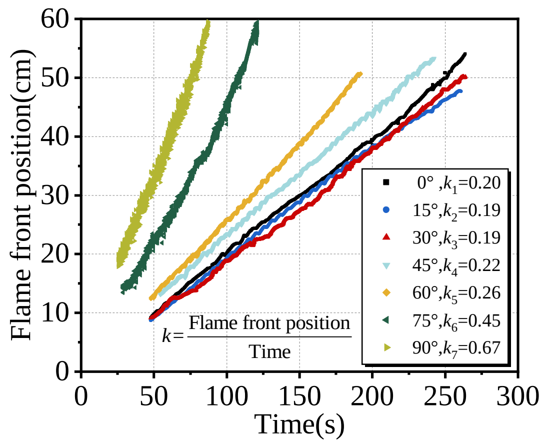
Figure 10 Variations of flame tilt angle β at different inclination angles.

3.3 Flame Spread Rates (V_f)

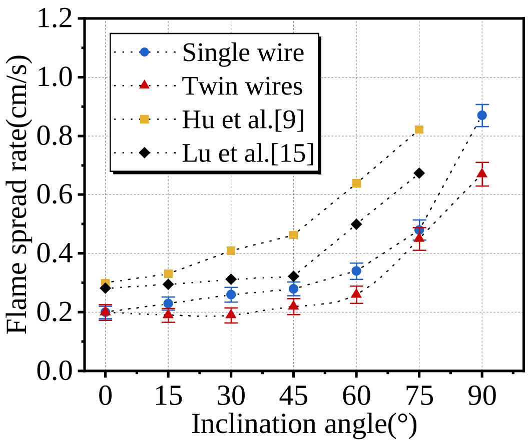
The variation of the flame front position as the function of time at different inclination angles for single-wire and twin-wire conditions were shown in Figure 11(a) and (b), respectively. The flame front position is automatically acquired by the image post-processing computer software, which is successfully used in previous work [40, 53, 54]. In general, the flame front position increases linearly with time, although its fluctuations increase as the inclination angle, especially for the vertical configuration. As is well known, the upward flame spread is typically acceleratory, and can achieve a steady state for sufficiently large test samples [49, 51]. Nagachi et al. [49] found that the concurrent flame spread could achieve a steady state over wire with 116 mm length in microgravity, but not in normal gravity. Moreover, Lu et al. [15] reported linearity of flame front motion and its steady spread over electrical wire with different inclination angles (0°~90°). Therefore, the flame spread rate V_f can be determined by the increasing rate of the flame front position, which is similar to the method in previous work [15]. Figure 11(c) plots the variations of V_f as a function of inclination angle, in which the comparisons of V_f in this paper with the results of Hu et al. [9] and Lu et al. [15] are also performed for verification. Overall, the change of V_f over a single wire shows a similar trend with the referred tests. For either single- or twin-wire conditions, V_f shows a sharp increase when $\theta \geq 60°$. By comparing the inclined V_f between two wire arrangements, we found that V_f in twin-wire conditions is slightly lower than that of single-wire conditions. One of the reasons can be explained by the incident heat flux from the flame to the insulations, referring to the theoretical analysis by Hu et al. [9]. There is an overlapped area of two insulations in twin-wire arrangement, which causes the insufficient heat flux from the flame to each wire insulation. It can be reflected by the flame tilt angle as well. It is notable that at the inclination angle from 0-30°, the averaged V_f can be even lower with the inclination angle increases, which can be explained that when tilted from 0 ° to 30 °, there is a transition from molten dripping to sliding, and the frequency of sliding is greater than the frequency of dripping.



(a) Time-dependent flame front position in single-wire conditions



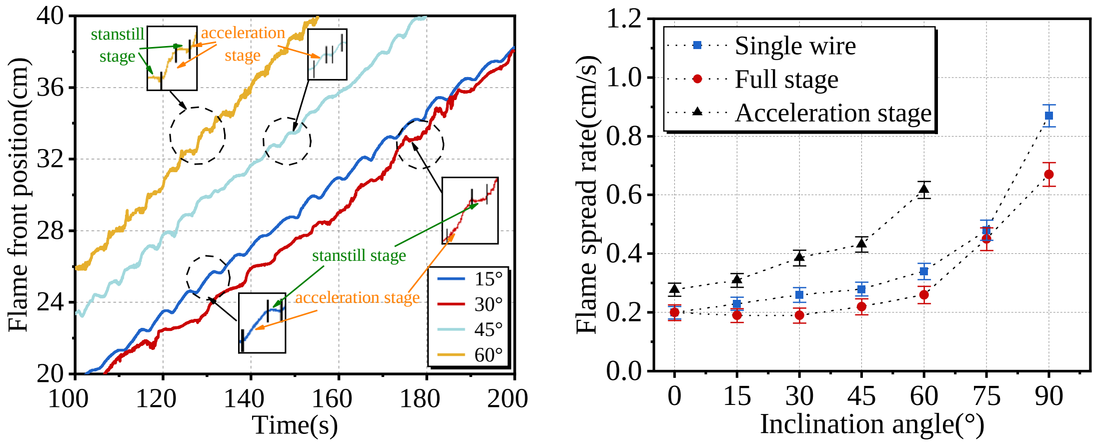
(b) Time-dependent flame front position in twin-wire conditions



(c) Flame spread rates (V_f) at different inclination angles

Figure 11 Variation of flame front positions and flame spread rates (V_f) at different inclination angles.

It can be seen from Figure 11 (a) and (b), the flame front increases basically linearly with time for single wire conditions. The overall flame front growth is also linear for twin-wire conditions, but it experiences periodic fluctuations in detail. Figure 12 (a) shows a partial magnification for flame front as a function of time for typical inclination angle over twin-wire conditions. Notably, the flame front position shows a periodic step change with time, especially when the inclination angle does not beyond 60°, which is due to the molten dripping and sliding, as well as the periodic fluctuations of flame length and flame height. Before molten dripping or sliding occurs, the insulation molten accumulates and the flame volume is enlarged, and consequently the flame front accelerates rapidly. In this stage, the flame spread rate is larger than that for the full stage, corresponding to acceleration stage. When molten dripping or sliding occurs, the flame volume decreases dramatically and the heat feedback to the PE insulation is reduced, resulting in the flame front spreading slowly or even to a standstill. In this stage, the flame spread rate is much less than that for the full stage, or even standstill, corresponding to standstill stage. Combing with the molten dripping or sliding frequency in Figure 4, the flame spread fluctuation can be synchronized with the molten dripping or sliding phenomena. The flame spread rates for every acceleration stage are calculated by reading the partial magnification of flame front and the average value is selected as the average flame spread rate at acceleration stage. Figure 12 (b) plots the comparison of average flame spread rate at acceleration stage and full stage for twin-wire conditions, as well as the flame spread rate for single-wire conditions. Because the frequency of molten sliding is too fast under the conditions of 75° and 90° inclination angle, the average flame spread rate at acceleration stage is not summarized in Figure 12 (b). It is obvious that the flame spread rate for single-wire conditions is slightly larger than that in full stage for twin-wire conditions, whereas it is significantly smaller than that at acceleration stage for twin-wire conditions. This observation also indicates that the molten dripping or sliding is essentially related to the flame spread over electrical wires and also has the effect of reducing the flame spread rate.



(a) Partial magnification for flame front as a function of time

(b) Comparison of flame spread rate at full and acceleration stage

Figure 12 Partial magnification for flame front and the V_f at full and acceleration stage, (a) Partial magnification for flame front as a function of time, (b) Comparison of flame spread rate in full and acceleration stage.

Moreover, according to previous work [13], the upward flame spread for single-wire and twin-wire conditions can be simplified as:

$$V_f \propto L_f \tag{2}$$

The relationships between L_f and V_f for single-wire and twin-wire conditions are presented in Figure 13 with the comparison of referred tests [15]. The values of Adj. R-Square of fitting linear for single-wire conditions is greater than 0.98, which demonstrates that the experimental results are consistent well with the referred theoretical analysis. Besides, the average flame spread rate of twin-wire conditions at the acceleration stage is also consistent well with Eq. (2) and the linear fitting coefficient is slightly larger than that of single-wire conditions, which implies that the theoretical coefficient could be applied to the condition of multi-wires without dripping or sliding. Therefore, the upward flame spread V_f for single-wire and twin-wire conditions can be expressed in terms of the characteristic length as $V_f \propto L_f$. However, due to the molten dripping behaviors in twin-wire conditions, the linear fitting coefficient of twin-wire conditions should be updated considering the decay stage of flame spread. The linear correlation between the flame spread rate and flame length can be applied for both single- and twin-wire conditions, but the coefficient should be updated considering not only the incident heat flux difference but also the dripping phenomena associated with the flame spreading.

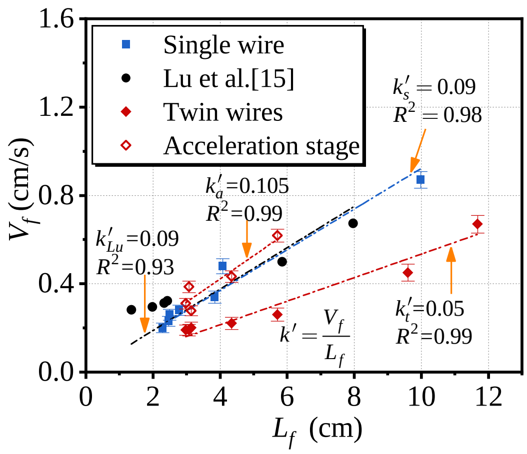


Figure 13 The relationship between L_f and V_f.

To our knowledge, the flame spread over solid surface is directly related to the heat feedback [9]. Figure 14 shows a simplified heat transfer process for electrical wires with a high conductive metal core, which is basically similar to previous work by Hu et al. [9]. The electrical wire can be divided into four distinct regions, including unburned zone, preheating zone, burning zone, and burned zone. According to work by Hu et al. [9], several assumptions are applied to simplify the system, shown as follows: (1) the temperature profiles across the cross-section of PE and metal core are assumed to be uniform; (2) the thickness of insulation remains the initial value by ignoring the complex shape change due to melting; (3) the temperature distribution along the wire core surrounded by the flame is steady; (4) the wire surrounded by the flame is assumed as the thermal isolation; (5) neglecting the axial heat conduction through the PE insulation; (6) The Nusselt number (*Nu*) is assumed to be the same constant for the single- and twin-wire conditions. Therefore, the heat conservation between the flame and the wire can be determined by the following equations [9]:

$$\dot{Q}_{fp}+\dot{Q}_{fc}=\pi(r_0^2-r_c^2)\rho_p V_f[c_p(T_p-T_0)+L]+\pi r_c^2\rho_c c_c V_f(T_p-T_0) \tag{3}$$

where $\dot{Q}_{fp}$ and $\dot{Q}_{fc}$ are the heat convection from the flame to the insulation and the heat convection from flame to the core, r_0 and r_c are the radius of the wire and the bare core; ρ and c are density and specific heat, the subscripts c and p denote core and insulation, T_p and T_0 are the pyrolysis temperature of insulation and ambient temperature, respectively, L is the latent heat of pyrolysis of the thermal insulation material (254 kJ/kg for PE [9]).

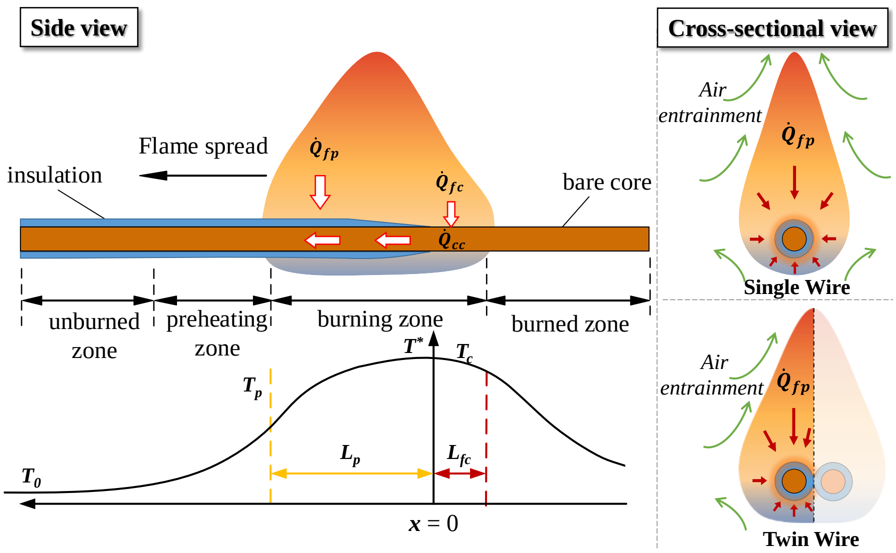


Figure 14 A simplified heat transfer model of wires with a high conductive metal core.

Moreover, $\dot{Q}_{\mathrm{fp}}$ and $\dot{Q}_{\mathrm{fc}}$ can be calculated as follows [9]:

$$\dot{Q}_{\mathrm{fc}}=2\pi r_c h_c L_{fc}(T_f-T^*) \tag{4}$$

$$\dot{Q}_{\mathrm{fp}}=2\pi r_0 h_0 L_p (T_f - T_p) \tag{5}$$

where h_c and h_0 are the heat transfer coefficient from flame to the bare core and the insulation, h_c and h_0 are the heat transfer coefficient from flame to the bare core and the insulation, which can be determined by $h = Nu\lambda_g/d$, where Nu~0.8 for nature convection in this work as similar to previous work [9]; λ_g is the thermal conductivity coefficient of air, and d is the diameter of the wire or the metal core. L_{fc} and L_p are the lengths of the bare core surrounded by the flame and the pyrolysis zone part, T_f is the flame temperature, which can be considered as a constant of 1100 K obtained by experiments and is slightly less than the results in literature by Hu et al. [9]. Besides, T^* is the temperature of the demarcation region between insulation and core, which can be expressed by [9]:

$$T_f - T^* = \frac{T_f - T_p}{\frac{2h_c L_{fc} L_p}{\lambda_c r_0}+1} \tag{6}$$

Substituting Eqs. (4)-(6) into Eq. (3), the flame spread rate V_f over electrical wire can be calculated as [9]:

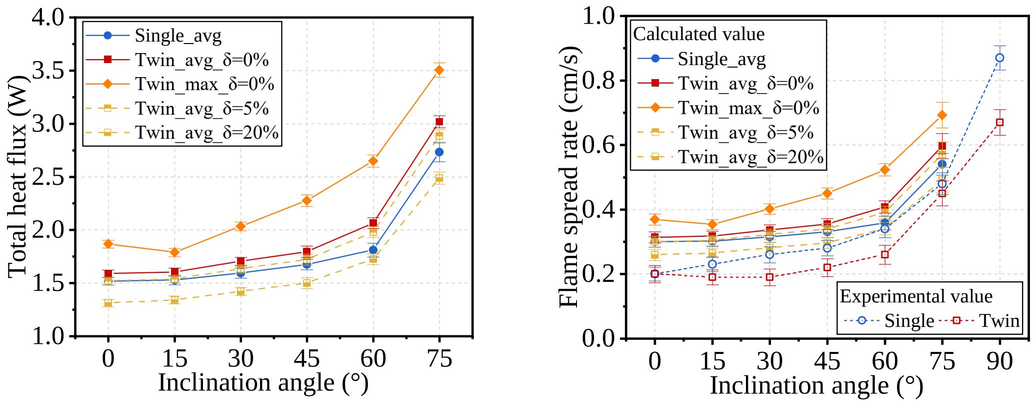
$$V_f = \left[2h_0 r_0 L_p + \frac{2h_c r_c L_{fc}}{\frac{2h_c L_{fc} L_p}{\lambda_c r_c}+1}\right] \cdot \frac{(T_f - T_p)}{\rho_p (r_0^2 - r_c^2)[c_p (T_p - T_0) + L] + r_c^2 \rho_c c_c (T_p - T_0)} \tag{7}$$

Obviously, the heat feedback and flame spread rate are controlled by L_p and L_{fc}, as well as h_c and h_0. For single wire conditions, the fuel surface is not overlapped and there is no obvious molten dripping or sliding in flame spreading process, the Eq. (7) can be applied to predict the flame spread rate. Whereas, for twin-wire configurations, there is an overlapped area of insulation layers, and the molten dripping or sliding behavior is observed. When the effects of overlapped area are considered, the Eq. (7) can be converted to the following form (ignoring the effects of molten dripping and sliding):

$$V_f = \left[2h_0 r_0 L_p (1-\delta) + \frac{2h_c r_c L_{fc}}{\frac{2h_c L_{fc} L_p}{\lambda_c r_c}+1}\right] \cdot \frac{(T_f - T_p)}{\rho_p (r_0^2 - r_c^2)[c_p (T_p - T_0) + L] + r_c^2 \rho_c c_c (T_p - T_0)} \tag{8}$$

where δ is the negative effects of overlapped area on the heat and mass transfer from flame to insulation, which mainly includes the following aspects, as shown in Figure 14: (1) the effective area of incident heat flux to one of the twin wires could be reduced due to the overlap of the insulation, resulting in a non-uniform heat flux on the wire surface; (2) since the flame is fully merged due to the two closely adjacent wires, the air entrainment to the flame per wire could be weakened, contributing to a lower average burning rate compared to the single-wire condition.

Figure 15 shows a comparison of total heat flux and flame spread rate predicted by Eq. (7)-(8) and the experimental results, in which the effects of overlapped area δ are considered as different values. In Figure 15, "avg" means the averaged value in the steady stages, and "max" means the maximum value in the acceleration stages of the twin-wire flame spread, referring to the cycle-averaged values of L_p and L_{fc} in the steady- and acceleration-stage defined in Figure 6, respectively. Considering the error caused by the determination of the flame temperature, the error bar in Figure 15 is calculated from the flame temperature of 1100 ± 50 K. It can be seen that for both single and twin wire conditions, the variation trends of the predicted flame spread rate as a function of inclination angle are in agreement with the experimental data but are larger than the experimental data. For twin wire conditions, the predicted total heat flux and flame spread rate corresponding to the maximum flame length just before the molten dripping or sliding occurs are obviously larger than that in the steady stage, which are consistent with the experimental observation in Figure 12. This investigation also directly demonstrates that when molten dripping or sliding occurs, the droplet would take away an amount of heat and the flame volume is obviously reduced, leading to the decreases in heat transfer and consequently the flame spread rate. Besides, the predicted total heat flux and flame spread rate corresponding to the average flame length with δ = 0 for twin wire conditions are still greater than that for single wire conditions, which is contrary to the experimental results. These opposite variations should be attributed to the effects of molten dripping/sliding and overlapped area. On the one hand, the flame is relatively small after molten dripping or sliding occurs for a period, and the flame front spreads slowly or even to a standstill, as can be seen from Figure 12. On the other hand, due to the existence of overlapped area effects (for δ = 5% and δ = 20%), the total heat flux received by wires would decrease, and correspondingly the flame spread rate would reduce, as shown in Figure 15. These effects result in that the flame spread rate at full stage for twin wire conditions is lower than that of single wire conditions, which demonstrates that the application of Eq. (7) to describe the flame spread rate over electrical wire should consider the effects of molten dripping/sliding and overlapped area.



(a) Total heat flux (b) Flame spread rate

Figure 15 Comparisons of predicted total heat flux and flame spread rate with the experimental results, (a) total heat flux and (b) flame spread rate.

4. Conclusions

The upward flame spread and molten dripping or sliding behaviors over single or adjacent electrical twin wires with different inclination angles were investigated experimentally. The trends of key parameters of flame spread as a function of the inclination angle, such as flame lengths, flame heights, flame angles and flame spread rates were observed, and these parameters of single-wire and twin-wire conditions are quantitatively compared. Interestingly, for twin-wire conditions, the flame length, the flame height, and flame spread rate grow periodically with time due to the molten dripping or sliding. Besides, the effects of the molten dripping or sliding on these parameters were discussed, especially on the spread rate. However, the molten dripping/sliding and flame spread behaviors are influenced by the wire diameter and insulation layer thickness, which will be in progress to investigate in the further studies. Besides, the relative position of the wires and separation distance could also potentially influence the inclined flame spread, which will be studied in future work.

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