STUDY ON COMBUSTION AND FLAME MERGING CHARACTERISTICS OF TWO N-HEPTANE LINE FIRES UNDER WIND SPEED, SPACING AND GROOVE WIDTH

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This paper studied the effects of wind speed, spacing and groove width on the combustion and flame merging characteristics of two n-heptane line fires. The experimental results show that the range of intermittent merging stage will increase with groove width; the greater the wind speed, the greater the probability of merging. At the non-merging stage, the influence of wind speed on the flame merging probability can be ignored. Under the influence of wind speed, $\dot{m}''$ *of the downstream pool fire is greater than that of the upstream pool fire, at the stages of fully merging and intermittent merging. While when the flame spacing increases to the non-merging stage,* $\dot{m}''$ *of the upstream pool fire begins to be gradually greater than that of the downstream pool fire. On the other hand, the downstream flame* $\dot{m}''$ *increases firstly and then decreases, while the upstream flame* $\dot{m}''$ *shows an increasing trend, with spacing distance. The smaller the groove width, the greater the value of* $\dot{m}''$*. When the spacing is 0,* $\dot{m}''$ *is the smallest. It is found that with the increase of spacing, the flame length under all tested conditions increases firstly and then decreases, and the flame inclination angle decreases firstly and then increases.*

Key words*: line fire, flame merging probability, wind speed, flame spacing, mass loss rate per unit area*

1. Introduction

In actually, forest, oil pool and building overflow fires often burn with wind influence. The ambient wind provides additional oxygen for the combustion zone. The flame shape tilts to the downstream region, thus promoting combustible gas and air mixing and enhancing the thermal feedback involved in flame propagation [1]. At the same time, the inclined flame may increase the temperature of the surrounding fuel surface, ignite the fuel and accelerate the flame propagation [2-4]. Thus, the coupling of airflow, heat transfer and combustion between flames is much more complicated [5-7]. These have brought new challenges to the emergency response, fire control and rescue [8]. For example, the Liangshan forest fires in China in 2019 and 2020, which caused heavy casualties, due to the sudden wind direction change during the burning. Thus, it is very important for predicting the development and behavior of such fires under the influence of wind.

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Many researchers have carried out extensive research on multiple pool fires of various shapes with wind or not. Huang *et al*. [9] studied the merging behavior and flame height of two jet flames at different burner distances. Liu *et al*. [10] revealed the interaction of two parallel line fires with a length-width ratio greater than 50 and compared it with single-line fire. Wan *et al*. [11] found that the flame burning rate and flame height changed monotonously with the increase of spacing for two identical square n-heptane pool fires. Liu *et al*. [12] studied the effect of gap height (the distance between the fuel surface and the upper edge of the fuel pool) on the thermal feedback and combustion emission mechanism of n-heptane pool fires. Ji *et al*. [13] used propane as fuel to study the interaction behavior of two jet flames under different burner spacing distances. Li *et al.* [14] investigated the characteristics of flame merging and inclination by using double propane burners with the same heat release rate parallel to the crosswind. Chen *et al*. [15,16] experimentally analyzed the flame interaction and behavior of two adjacent hydrocarbon turbulent diffusion flames under different transverse airflow rates and separation distances. Tang *et al*. [17,18] demonstrated the effects of crosswind and burner aspect ratio on the flame evolution and flame interaction characteristics on rectangular burners. Yao *et al*. [19] investigated the effect of wind on the mass loss rate per unit area of the pool fire in open environments and tunnels. The effect of transverse airflow on flame height evolution of two adjacent hydrocarbon pool fires was characterized in [20]. On the other hand, Huang *et al*. [21-23] experimentally and theoretically revealed the factors of spacing, fuel mass thickness, heat release rate and groove width on the flame merging over larger ratio of line fires, which can give practical suggestions for the use in the fire control and fire detection. However, the wind is not involved.

In summary, the relevant experiments carried out by the predecessors are mainly aimed at square and rectangular pool fires, or line fires with small aspect ratio. And the research on multi-factor coupling is very rare. Therefore, the purpose of this paper is to comprehensively consider the influence of wind speed, spacing and groove width on the flame merging over two line fires with large aspect ratio. The expected results can better predict the merging state in real fire scenarios (such as forest and oil pipeline leakage fires), and enrich the content of fire research of double-line pool fires.

In this paper, the U-shaped grooves were designed with widths of 0.5, 1 and 1.5 cm, height of l cm, and 20 cm length, respectively. The burning liquid fuel n-heptane can be filled the groove to form a line pool fire. And then two identical line fires were studied with different spacing distances (0, 5, 10, 15, 17.5, 20, 22.5, 25 and 30 cm) and wind velocities (0.25, 0.5 and 0.75 m/s). The parameters such as flame length, flame inclination angle, flame temperature, and mass loss rate were obtained. The law of combustion and merging behaviors between two line fires was analyzed based on these parameters.

2. Experimental

As shown in fig. 1, this paper realizes different wind speed conditions through self-made small wind tunnel. By controlling the power of the axial flow fan and after that through the rectifier section, the experimental wind velocities were set at 0.25, 0.5, 0.75 m/s, respectively. Before the experiment, an AR866A high-precision thermal anemometer was used to measure the wind speed at the experimental section. The mass loss rate was measured by an electronic balance at the range of 0~ 6000 g, and the accuracy was 0.01 g. A piece of gypsum board was placed between the electronic balance and the two parallel burners for thermal insulation. The burner spacing was set at 0, 5, 10, 15, 17.5, 20, 22.5, 25 and 30 cm. Camera instruments were arranged at the front and left side of the experimental facility to record the combustion process.The flame temperature was measured by a set of five K-type thermocouples at 10 cm intervals which was placed upon the each burner, respectively. The temperature history was recorded by a data collector linked to a computer. The measured temperature range was at 0 °C to 1200 °C and the measurement error was less than ±1.5 °C.

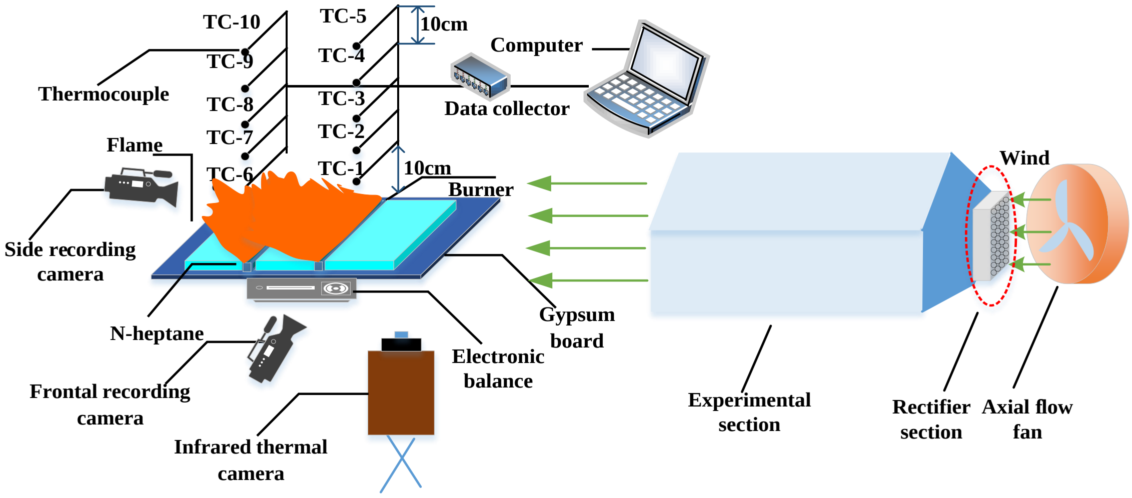


Figure 1. Experimental equipment diagram

Table 1 gives the specific test conditions. There are 81 tests which were carried out totally. For W=0.5, 1 and 1.5 cm, 6, 12 and 18 g of n-heptane fuel were used to fully fill each burner, respectively. And the selected spacing was 0, 5, 10, 15, 17.5, 20, 22.5, 25 and 30 cm, and the chosen wind velocity was 0.25, 0.5 and 0.75 m/s, correspondingly. The experiment in each case was repeated three times to reduce the errors.

Table 1. Test conditions

Test number	Initial single fuel mass [g]	Groove width(W) [cm]	Groove height [cm]	wind velocity(V) [ms^{-1}]	Spacing distance (S) [cm]
1-9	6	0.5	1	0.25	0, 5, 10, 15, 17.5, 20, 22.5, 25, 30
10-18	6	0.5		0.5	
19-27	6	0.5		0.75	
28-36	12	1		0.25	
37-45	12	1		0.5	
46-54	12	1		0.75	
55-63	18	1.5		0.25	
64-72	18	1.5		0.5	
73-81	18	1.5		0.75	

The experiments were conducted in Ma’anshan (China) plain, with the normal conditions as shown in tab. 2. Obviously, the burning intensity and combustion characteristics will be greatly influenced by the atmosphere, oxygen concentration, humidity and environment temperature for the specific location.

Table 2. Geographical and meteorological conditions in Ma’anshan

Altitude[m]	Atmosphere[kPa]	Oxygen concentration[kgm^{-3}]	Humidity[%]	T_∞[°C]
50	101.8	0.269	55	15-20

2.1. Uncertainty Error analysis

In this research, in order to calculate the uncertainty errors in the experimental results, the method proposed by Moffat [24] was used. It can be described as: $X_{total} = (X_1^2 + X_2^2 + ... + X_n^2)^{1/2}$, where X_n presents the component error, and n is the total number of error components. Eventually, the total error X_{total} will be calculated. Table 3 shows the uncertainty analysis of measured parameters involved in this paper.

Table 3. Error analysis of all measured parameters

Parameters	Error components	Error components value	Total error value
P_m	experimental error	±3%	±5%
	statistical error	±4%	
L	experimental error	±2%	±4.7%
	measurement error	±4.3%	
θ	experimental error	±2%	±5.9%
	measurement error	±5.6%	
$\dot{m}''$	experimental error	±2%	±3.6%
	measurement error	±3%	

3. Results and discussion

3.1. Flame shape

As depicted in fig. 2, the flames on two burners tilt to the left under different wind speeds, spacing distances, and groove widths. Notably, the inclination becomes more pronounced with the higher wind speed. It can be seen from the picture that the flame shows a bright yellow color due to insufficient combustion. As n-heptane has a high carbon content, so the combustion produces many soot particles. Meanwhile, the flame inclination angle decreases with the increase of the pool width. For different wind speeds, the flames show a fully merging state when the flame spacing is small at 0-5 cm. While when the flame spacing gradually increases to 10-25 cm, the stage changed to the intermittent merging state. The upstream flame is subjected to a relatively stronger wind force, compared with the downstream flame, and the flame length is smaller. When the flame spacing increases further, the upstream and downstream flame lengths and tilt angles begin to approach to each other. It can also be observed that with the increase of wind speed, the flame merging probability of the fires will increase.

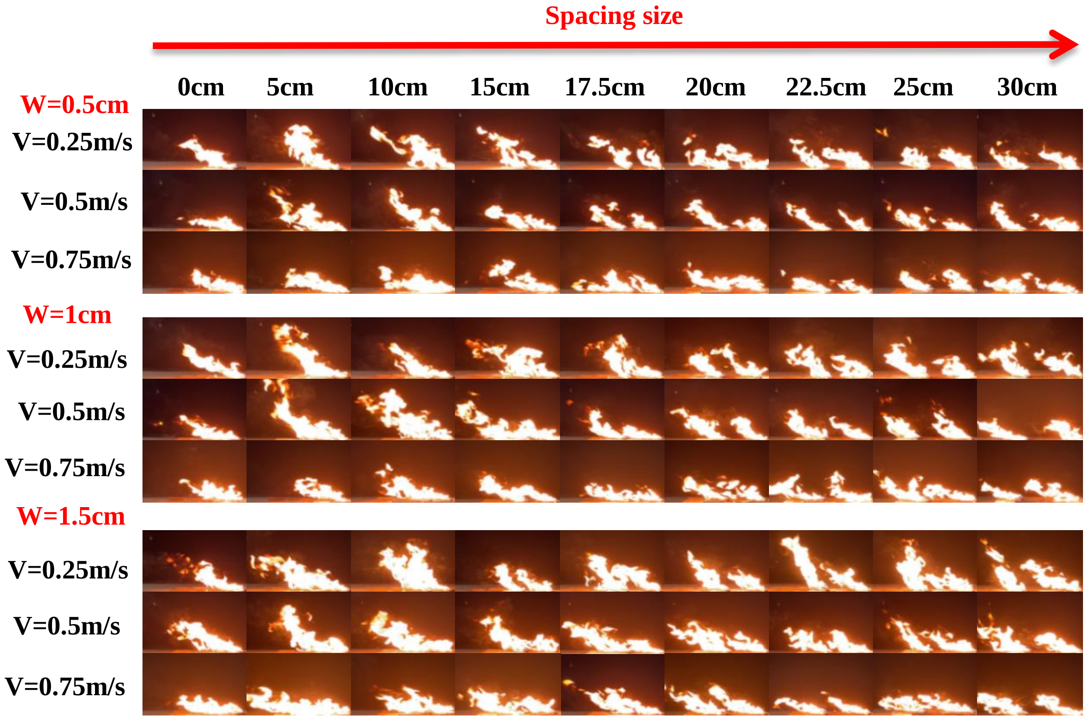


Figure 2. Flame shape for V, S and W

3.2. Flame merging probability

Figure 3 gives the flame merging contour vs W,V and S. First, a video of 60 seconds is intercepted at the stable burning state.Then it is converted into 1500 images with the frequency of 25 per second by Adobe Premiere software. After that, a series of original images was converted into gray images, and then to binary images. Calculated by Otsu method using self- programming in Matlab [25], the flame merging contour of the integrated images can be obtained.

According to the previous description of the flame merging probability, P_m is defined as [26]:

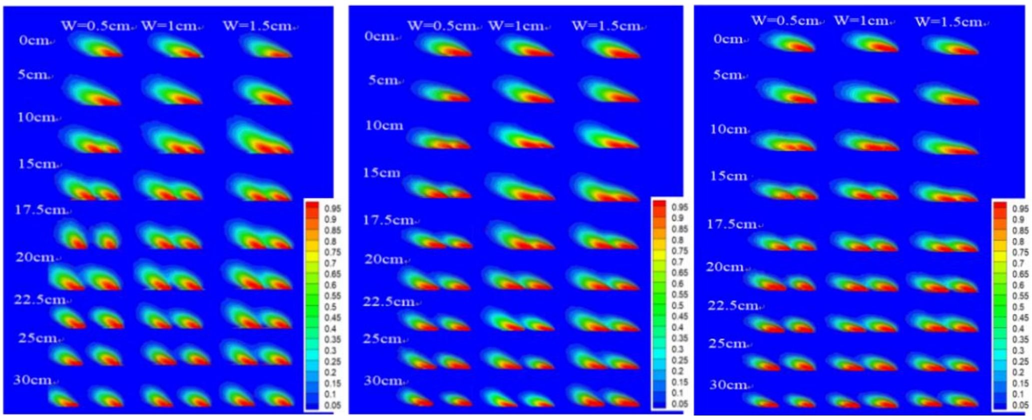
$$P_m = 1/(1 + exp((S/Z_c) - a)/b) \quad (1)$$

where a is the value of S/Z_c when P_m=0.5, b represents the slope of the curve, and Z_c is the feature length. In this paper, the flame merging probability P_m is defined as the maximum value of the two contacted flame intermittency contours, which is based on the image treatment. On the other hand, it can also be calculated according to the formula of Thomas *et al.* [27], given as follows:

$$P_m = \frac{1}{1 + e^{(A.S_x + B.S_x^2 + C.S_y + D)}} \quad (2)$$

where S_x and S_y represent the dimensionless horizontal width and dimensionless vertical width after normalization. A, B, C, D are the predicted coefficients of the fitted curves, respectively.

When the spacing distance is 0-5 cm, the two fires are basically completely merged. Due to the small flame spacing, under the influence of wind force, the merged flame is similar to a single flame. When S=10 cm, the center of the merged flame begins to appear empty. At this time, the flame is affected by the lateral airflow into the empty area, resulting in the instability of the left and right fires. With the increase of S, the flame merging probability gradually decreases between 15 cm and 25 cm. And the area of the cavity at the bottom of the flame is also gradually increasing. When the flame spacing exceeds 25 cm, there is no merging phenomenon, but there is still a certain attraction between the two fires.



(a) V=0.25 m/s (b) V=0.5 m/s (c) V=0.75 m/s

Figure 3. Flame merging probability contour

The probability of flame merging (P_m) refers to the maximum probability of contacting of two line fires at the space, as given in fig. 4. For W=0.5 cm, the merging of two line fires can be divided into three states: (1) Fully merging, P_m=1, when S⩽5 cm; (2) Intermittent merging, 0.05<P_m<1, when S=5~25 cm; (3) Non-merging, P_m⩽0.05, when S>25 cm [19,28]. While for W=1.5 cm, when S=30 cm, it is almost at the intermittent merging state for the three different wind velocities. It can be predicted that with the increase in groove width, at the same spacing and wind speed, the probability of flame merging will increase. However, as the spacing increases to the non-merging state, it can be inferred that the influence of wind speed on the merging probability will gradually decrease, as the spacing distance is relatively large.

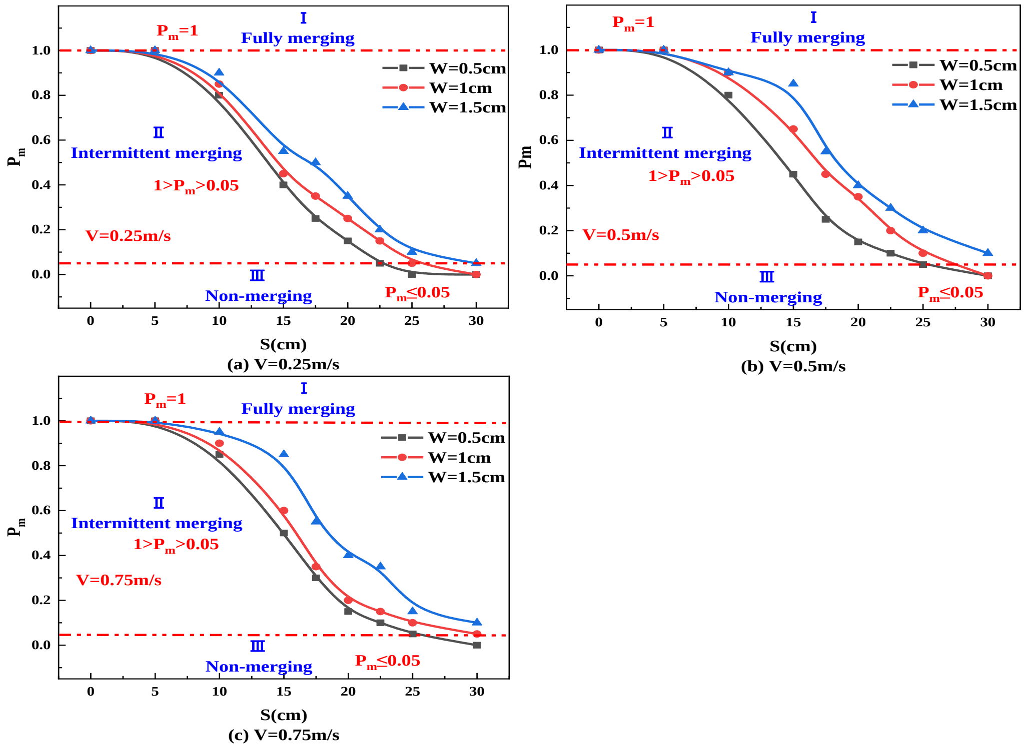


Figure 4. The flame merging probability vs Ws, Ss and Vs

Figure 5 shows the flame merging probability against spacing distance normalized by the flame height $S/L_{f,s=0}$ at S = 0. By linear fitting, the flame merging probability can be well related with $S/L_{f,s=0}$ at different stages.

When V=0.25 m/s, P_m at the intermittent merging stage corresponds to $S/L_{f,S=0}$, having:

$$P_m = -0.77(S/L_{f,S=0})+1.06 \qquad R^2=0.85 \tag{3}$$

When V=0.5 m/s：

$$P_m = -0.82(S/L_{f,S=0})+1.16 \qquad R^2=0.92 \tag{4}$$

When V=0.75 m/s：

$$P_m = -1.01(S/L_{f,S=0})+1.28 \qquad R^2=0.92 \tag{5}$$

The slope of the fitting curve increases with the wind speed, indicating that the larger wind speed will lead to the increase of the flame merging probability, which is consistent with the analysis above. On the other hand, the slopes obtained are obviously smaller than those in reference [14] about the rectangular burners. Thus, the flame merging will be weakened for the line fires. Meanwhile, it can be seen that for V=0.25, 0.5 and 0.75 m/s, the critical distance $S/L_{f,S=0}$ of flame merging is 1.53, 1.45 and 1.27, respectively. With the increase of wind speed, $S/L_{f,S=0}$ shows a decreasing trend, which also indicates that the increase of the wind speed will increase the flame merging.

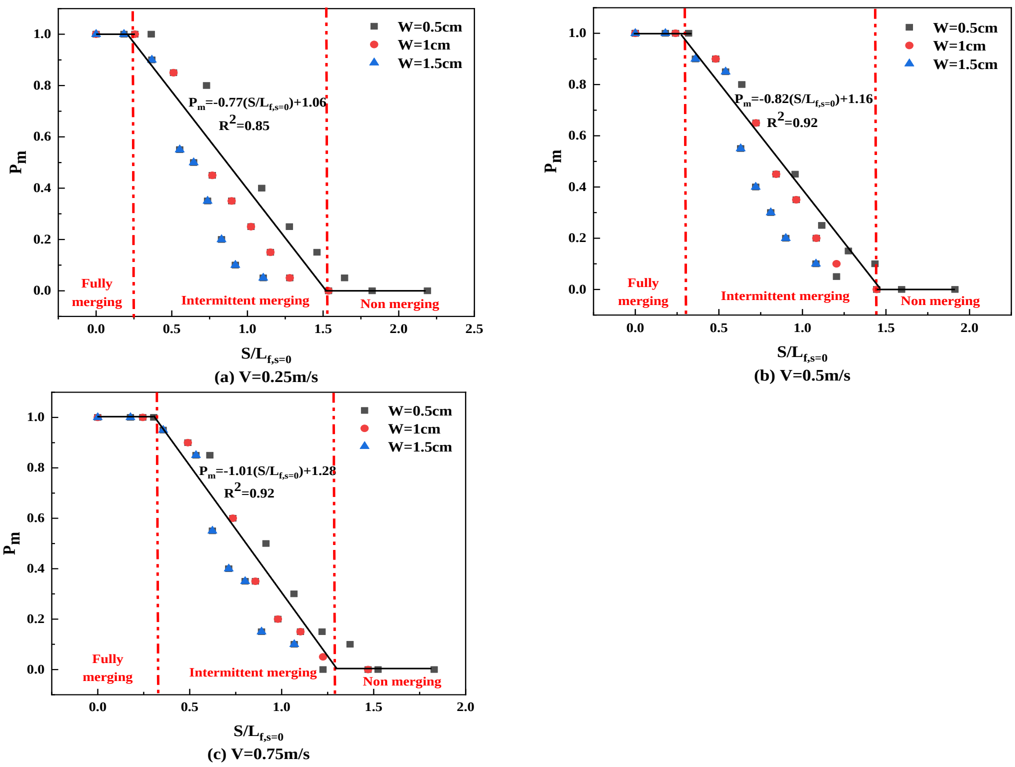


Figure 5. Correlation of P_m and $S/L_{f,S=0}$

3.3. Flame length and flame inclination angle

Flame length is an essential parameter for studying flame combustion characteristics. As shown in fig. 6, the flame length is defined as the distance from the surface of the fuel to the flame tip with the flame merging probability of 0.5 for the downstream and upstream fires, respectively [29].

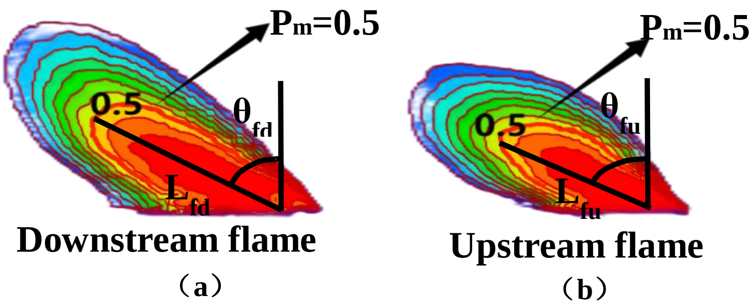


Figure 6. Definitions of flame length and inclination angle

Figure 7 shows the flame length with different widths, spacing distances and wind speeds. Under the same wind speed and spacing, the flame length increases with the increase of groove width for downward and upward flames. The minimum flame length appears almost at the spacing of 15-20 cm, which represents the wind effect is weakened at the largest. When the spacing is 0-5 cm, the flame is at the fully merging stage. Especially at S=5cm, the flame length is relatively large due to the effective merging burning. When the spacing gradually increases to the intermittent merging stage, the gap between the flames begins to appear. The effects of the transverse airflow and gap air entrainment will influence each other greatly, making the flame length decrease. While at the non-merging stage, the spacing is relatively large, the flame interaction will gradually weakened. Eventually the flame length will increase slightly. It can also be found that, the upstream flame length is almost smaller than that of the downstream. This is because that, the upstream flame is greatly affected by the transverse airflow, making some of the evaporated combustible gas out of the burning. While for the downstream flame, with the hindrance on the wind of the upward flame, the flame length is larger with the effective burning.

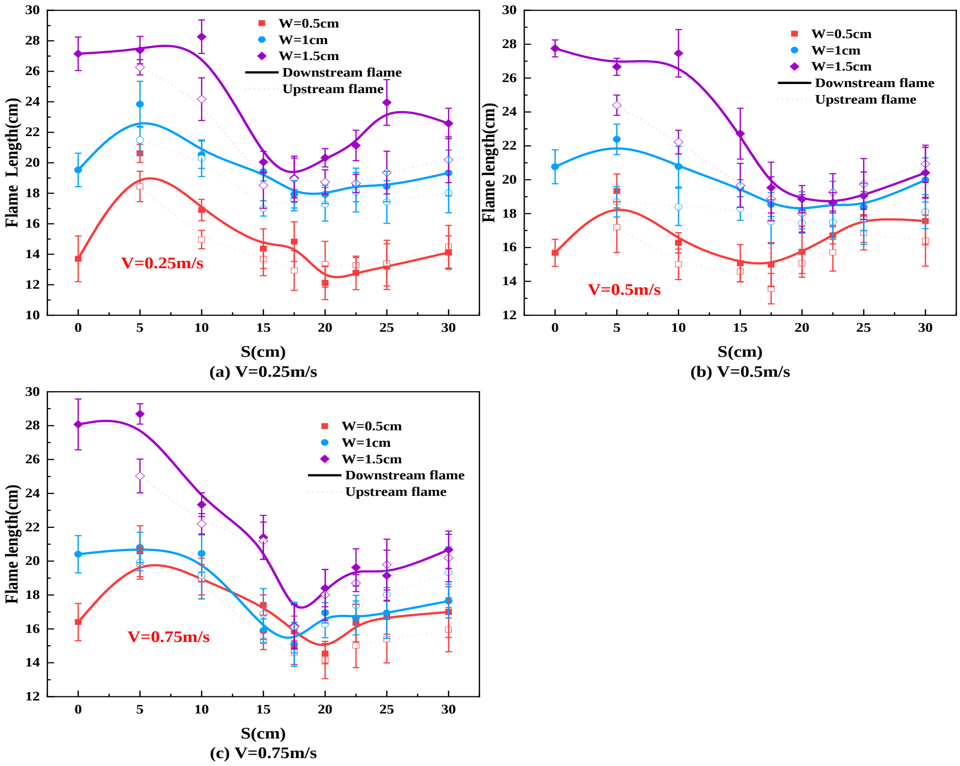


Figure 7. Flame length against W, S and V

The flame inclination angle θ is defined as the angle between the flame length line and the vertical direction line as shown in fig. 6. Figure 8 gives the flame inclination angle with different widths, spacing distances and wind speeds. Overall, the flame inclination angle decreases first and then increases and finally tends to be stable. The lowest point is between 15-20 cm, which has the same trend with flame length due to the influence of the transverse airflow and air entrainment in the gap. Moreover, the upstream flame is greatly weakened by the wind force, thus the inclination angle is larger than that of the downstream flame.

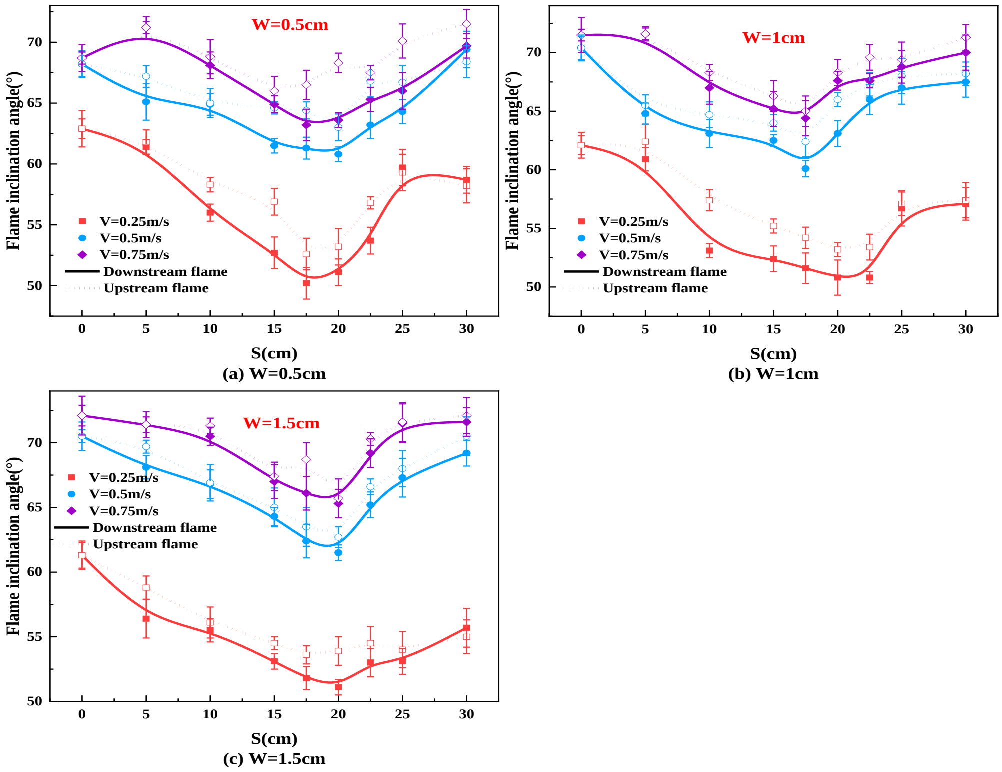


Figure 8. The flame inclination angle with different Ws, Ss vs Vs

3.4. Mass loss rate

Figure 9 shows the mass loss rate per unit area with different groove widths, spacing distances and wind speeds. The smaller the U-shaped groove width, the larger the $\dot{m}''$ at the same conditions. It demonstrates that the thinner line fires will be more easily controlled by the flame merging. When the spacing increases, $\dot{m}''$ of the downstream flame increases firstly and then decreases, but the upstream flame almost shows an increasing trend in the whole. Interestingly, when the spacing is 0, $\dot{m}''$ is the smallest, which can be considered that the complete merging will weaken the burning intensity. And when S≤22.5 cm, the upstream flame $\dot{m}''$ is smaller than that of the downstream flame. After that,the upstream flame $\dot{m}''$ is gradually larger. This illustrates that the downstream flame is mainly influenced by the flame interaction and flame merging, while the upstream flame is more affected by the wind.

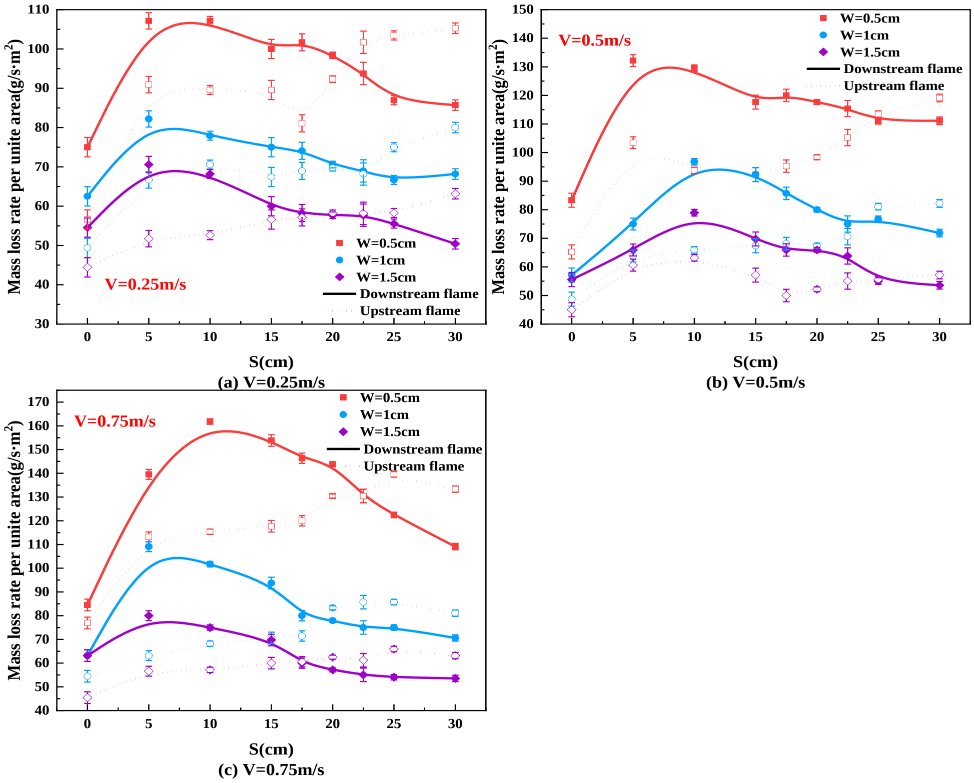


Figure 9. The mass loss rate with different Ws, Ss vs Vs

4. Conclusion

This study was conducted to investigate bilinear fires interaction and flame merging. The specific goal is to reveal the flame merging and combustion characteristics under different widths, spacing distances and wind speeds, and obtain the relevant flame parameters, such as flame length, flame inclination angle, mass loss rate, etc. The results can provide theoretical basis and fire prevention for the actual forest, oil pipeline leakage and other fires, and avoid serious casualties and property losses with great practical significance. The main conclusions as follows :

(1) The probability of flame merging decreases with the increase of spacing. And the greater the wind speed, the greater the probability of merging.

(2) The flame merging will be weakened for the line fires, compared to the rectangular fires.

(3) The minimum flame length appears almost at the spacing of 15-20 cm, as the effect of the wind was weakened at the largest.

(4) The upstream flame length is smaller than that of the downstream, due to the hindrance of the wind.

(5) The flame inclination angle is the smallest also at the spacing of 15-20 cm, which is consistent with the trend of the flame length.

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