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Transition from Surface Fire to Crown Fire and Effects of Crown Height, Moisture Content and Tree Flower

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Abstract. At present, most of the previous work focused on the effects of crown bulk density, crown base height, and wind on the initiation and behaviors of crown fire using tree branches. However, very few investigations have been carried out related to the initiation and behaviors of crown fire using a real tree considering moisture content, crown height and tree flower. In this paper, a series of burning experiments are carried out using real trees to investigate the effects of moisture content, crown height and tree flower on initiation conditions from surface fire to crown fire and crown fire behaviors. The variables of two crown heights (1.0 m, 1.5 m), three crown moisture contents (45 $\pm$ 2%, 55 $\pm$ 2%, 65 $\pm$ 2%) and tree flowers are selected. The main conclusions are as follows: when the tree has the higher crown base height and the larger moisture content, the crown fire initiation success from surface fire decreases, while the existence of tree flowers tends to lead to initiation success of crown fire. The critical fireline intensity can be used to determine the initiation of crown fire from surface fire for conditions with the absence of tree flowers, whereas the critical value can not be applied to cases with the existence of tree flowers. Moreover, the lower moisture content and higher crown height are, the maximum values of the flame height, fire plume temperature, and radiation heat flux of crown fire are larger. Besides, when the tree is covered with tree flowers, the flame height, fire plume temperature, and radiation heat flux of crown fire increase significantly due to the increases of fuel load and flammability. This work can not only provide theoretical basis for crown fire, but also supply technical guidance for the prevention and extinguishment of crown fire.

Keywords: Crown fire, Initiation condition, Crown height, Moisture content, Tree flower

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1. Introduction

Forest fire is one of the most severe natural disasters, which seriously threatens the ecology and safety of forests [1]. At present, more than 220,000 fires occur in the world every year, and more than 6.4 billion hectares of forests are burned and destroyed, which accounts for about 0.23% of the world's forest cover [2, 3]. For example, an Australian forest fire [4] occurred in January 2020 has burned more than 6.3 million hectares of forests and killed 25 people. The forest fire happened in southwestern China on April 1 2019, spread across over 1000 hectares and caused 22 firefighters' deaths. Hence the forest fire has gradually attracted considerable attention for decades because of high frequency and profound losses. It is well-known that forest fire can be generally categorized into underground fire, surface fire and crown fire [5]. Among them, the surface fire has the highest occurrence probability and frequency and is also the main trigger of crown fire [6, 7]. Whereas, the crown fires occur less frequently compared with surface fire, but they spread faster and are more difficult to control [8–11], which tend to result in much more damage than surface fire. Therefore, it is imperative to understand initiation conditions from surface fire to crown fire and behaviors of crown fire.

In recent years, a series of works had been performed to study the initiation conditions from surface fire to crown fire. Van Wagner [12] developed a simple semi-empirical model for crown fire initiation by utilizing the plume theory of convective heating to predict the minimum surface fire intensity to initiate crown fire. Grinshin and Perminov [13] numerically investigated the ignition process of a crown fire and quantitatively analyzed the distributions of temperature and pyrolysis gas component for initiation conditions from surface fire to crown fire. Xanthopoulos [14] developed an empirical ignition score model to predict crown fire initiation based on the hot plume temperature and time without considering the influence of moisture content. Tachajapong [15, 16] experimentally and numerically studied the effects of crown fuel base bulk density and wind on crown fire ignition from surface fire using chamise branches in an open environment. It was found that the crown fire initiation success decreased as the crown base height and wind, while the crown fuel temperature and crown fire initiation success increased with bulk density. Moreover, Tachajapong [17] revealed the wind effects on crown fire initiation with tree branches in open and closed shrubland systems, and demonstrated that increasing wind speed decreased the tendency of crown fire initiation in an open environment, but conversely the propensity for crown fire initiation increased with wind in a closed system. According to the references mentioned above, the effects of crown fuel moisture content on crown fire initiation from surface fire were rarely involved, especially using a real tree.

Recently, crown fire behaviors have been gradually studied as a classical problem. Ryan [18] first proposed a fire intensity model to quantitatively study the relationship between fire spread speed and flame height. The models for predicting the crown fire behaviors were developed by Van Wagner in Canada [19] and Rothermel [6] in USA taking the effects of wind velocity and crown bulk density into account. Albini [20] carried out a series of nine experimental wind-aided crown fires using immature Jack Pine and compared the spread rate of crown fire obtained in experiments with the predictions by a proposed model. Cruz et al. [21] investigated the spread rate of crown fires advancing over level to gently undulating terrain and found that the crown fire spread rate can be separately modeled into the active and passive crown fire. Mell et al. [22] conducted a series of crown fire experiments using an individual tree with different tree height and moisture content and put forward a numerical model to present the spatial distribution of vegetation in a tree crown. It was noted that the predictions of radiation heat flux and mass loss rate were shown to be consistent with experimental results. Hoffman et al. [23] utilized a set of experimental data to provide a coarse assessment of crown fire spread rate predictions by WFDS or FIRETEC. Zhou et al. [24] proposed an analytical model to predict the flame length of a line fire and tree crown scorching based on the physical processes of heat transfer and thermal response of needles and leaves. However, the most of previous work focused on the effects of crown bulk density and crown base height on the crown fire, but few investigations have addressed the dependence of the moisture content and crown height on crown fire behaviors. At the same time, the previous studies only focused on limited characteristics of crown fire such as flame height, but did not explore other parameters in detail of fire plume temperature, radiant heat flux, etc.

Besides, the field survey was carried out in the area where the forest fire occurred in Southwest China. Interestingly, many trees on the shady side are covered with tree flowers, as shown in Figure 1 by the red remark, which is a widespread phenomenon in forests. Tree flower is a kind of fungal parasitic plant, which grows on the trunks of trees at an altitude of about 1500 m in the mountains of southwest China. It is found that the tree flower is a flammable substance through the flammability tests in the laboratory. The existence of tree flowers will appreciably increase the fuel load of the tree, which may result in the increase in occurrence probability and damage degree of crown fires. Thus, it is necessary to investigate the effect of tree flowers on crown fire initiation from surface fire and crown fire behaviors.

In this paper, a series of burning experiments are performed using real trees to study the effects of crown height, crown moisture content and tree flowers on the crown fire initiation from surface fire and crown fire behaviors. The variables of two crown heights, three crown moisture contents and tree flowers are considered. The initiation conditions for the transformation from surface fire to crown fire and crown fire behaviors of flame height, radiant heat flow and fire plume temperature are analyzed and compared. This paper not only provides the theoretical basis for the research on the characteristics of crown fire, but also is very important for the better understanding of the problem of the crown fire.

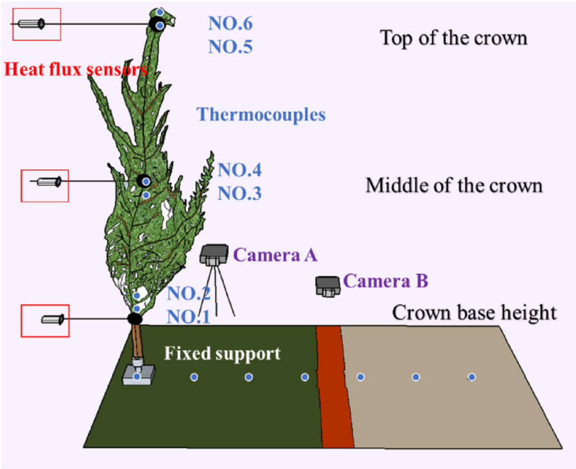
2. Experimental Setup

A laboratory-scale experimental setup for crown fire is schematically shown in Figure 2, which is composed of surface fire part and crown fire part. For the surface fire part, the surface fuel bed with the dimension of 0.75 m (width) × 1.5 m (length) is uniformly filled with 0.4 kg of Camphor leaves, which are conditioned

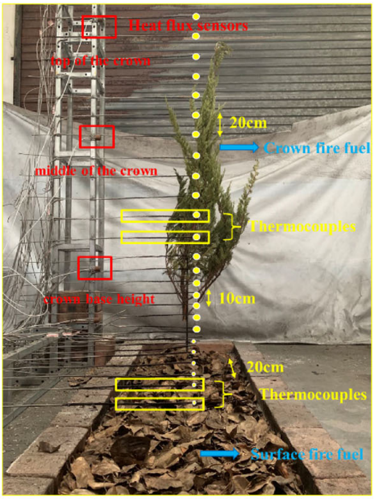
Figure 1. Trees covered with tree flowers.

in a drying oven for at least 24.0 h until the weights are kept constant before the experiments. Then 5.0 ml of ethyl alcohol is sprayed uniformly over the width of the surface fuel bed and consequently a line fire can be established to ignite the surface fuel along the width. For the crown fire part, a tree fixed support is used to adjust the crown base height flexibly. Cypress is selected as the tree species for crown fire experiments, which is abundant in southwestern China, where wildland fires are most prevalent.

To obtain surface fire spread rate, 7 thermocouples are arranged along the central line from 0.2 m to 1.4 m of the surface fuel bed with 0.2 m intervals, which are set 0.1 m above the surface fuels. In the vertical direction, the thermocouples are arranged with 0.1 m interval from surface fuel to crown base height and with 0.2 m interval from crown base height to 3.0 m to observe crown fire temperature. The thermocouples used in this paper have a temperature range and date collection interval of 0–1100°C and 1.0 s, respectively. Three heat flux sensors of model GD-B5-20 K are distributed in the following three positions: crown base height, middle of the crown and top of the crown to obtain the flame radiation heat flux,



(a) Schematic of experimental setup arrangement



(b) Physical of experimental setup arrangement

(c) Experimental tree covered with tree flowers

Figure 2. Experimental setup for crown fire.

which are set at a horizontal distance of 0.5 m from the tree. The measuring range and response time of heat flux sensors are 0–20 kW/m^2 and 250 ms, respectively. For burning experiments with different crown heights, the positions of the heat flux sensors should be adjusted before each experiment. To record the entire combustion process and flame geometry, two 4 K SONY cameras labeled FDR-AX60 with a resolution of 1920×1080 and a frame rate of 25 frames/s are set at a horizontal distance of 0.5 m from the center of the surface fuel bed and 0.5 m from the tree, respectively.

In order to investigate the effects of moisture content, crown height, and tree flower on initiation conditions and behaviors of crown fire, the variables of two crown heights, three crown moisture contents and tree flowers are considered. Trees of two different crown heights are used in burning experiments: approximately 1.0 m and 1.5 m. The relative moisture content of the crown is calculated by the following formula:

$$FMC = \frac{W_1 - W_2}{W_1} \times 100\% \tag{1}$$

where FMC is the relative moisture content of the combustibles, W_1(g) and W_2(g) are the wet weight and dry weight of the test tree species, respectively. The tree species are conditioned in a drying oven for different time to obtain the desired moisture content samples. After the desired moisture content is obtained, the burning experiments were conducted as soon as possible to reduce the effect of moisture content changes. In this paper, three moisture contents for tree species of 45 ± 2%, 55 ± 2% and 65 ± 2% are selected. Besides, to study the effects of tree flowers on the initiation and behaviors of crown fire, a mass of 50.0 g dried tree flowers are evenly distributed on the crown of tree species and not arranged below the crown base, as shown in Figure 2c. In order to avoid the moisture content effects of tree flowers on burning behaviors, the tree flowers are dried to constant weight before the experiment to ensure the same condition under each experimental condition. All experimental conditions are summarized in Table 1. All the experiments are performed in a large test hall in still air, in which the ambient temperature and relative humidity are 16 ± 4°C and 70 ± 3%, respectively.

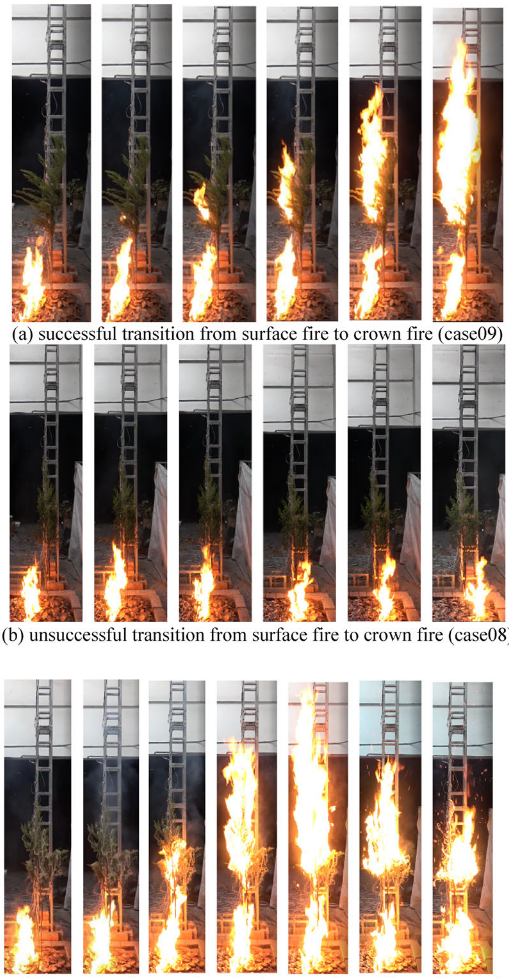
Table 1
Summary of Experimental Conditions

Case	Crown base height(m)	Crown height(m)	Moisture content(%)	Tree flowers
01	0.4	1.5	45 ± 2	No
02	0.4	1.5	55 ± 2	No
03	0.4	1.5	65 ± 2	No
04	0.5	1.0	45 ± 2	No
05	0.5	1.0	55 ± 2	No
06	0.5	1.0	65 ± 2	No
07	0.6	1.5	65 ± 2	No
08	0.7	1.5	65 ± 2	No
09	0.7	1.5	45 ± 2	No
10	0.7	1.5	65 ± 2	Yes
11	0.8	1.5	45 ± 2	No
12	0.8	1.5	45 ± 2	Yes

3. Results and Discussion

3.1. Initiation Conditions from Surface Fire to Crown Fire

Figure 3 plots the sequential images of successful and unsuccessful transitions from surface fire to crown fire. It can be found that the tree species with crown base height of 0.7 m and moisture content of 45 ± 2% can be successfully ignited by surface fire, whereas the tree species are failed to ignite by surface fire as the moisture content increases to 65 ± 2%. Interestingly, while the crown base height (0.7 m) and moisture content (65 ± 2%) remain constant, the tree species with



(a) successful transition from surface fire to crown fire (case09)

(b) unsuccessful transition from surface fire to crown fire (case08)

(c) successful transition from surface fire to crown fire with tree flowers(case10)

Figure 3. Sequential images of transition from surface fire to crown fire.

tree flowers can be successfully ignited by surface fire. The initiation results of crown fire from a surface fire are summarized in Table 2.

It can be seen from Table 2, the higher crown base height and the larger moisture content are, the crown fire initiation success from surface fire decreases. While the existence of tree flowers tends to lead to initiation success of crown fire. Scott [25] came up with a parameter of critical transition fireline intensity to determine the critical conditions for the initiation from surface fire to crown fire. When surface fireline intensity in experiments is greater than the critical transition fireline intensity, the initiation of crown fire will occur. The critical transition fireline intensity can be expressed by the following equation:

$$I_0 = \left[\frac{CHB(460 + 25.9FMC)}{100}\right]^{\frac{3}{2}} \tag{2}$$

where I_0(kJ/(m·s)) is the critical transition fireline intensity, CBH(m) is the crown base height, FMC(%) is crown moisture content. Moreover, Byram [26] proposed a modified equation to calculate the surface fire fireline intensity in the experiments, as shown by follows:

$$I = HWR \tag{3}$$

where I(kJ/(m·s)) is fireline intensity in experiments, H(kJ/kg) is combustion heat of surface fuel, which is 10554 kJ/kg for Camphor leaves measured by professional laboratory experiments, W(kg/m^2) is the effective combustion mass, which is the subtraction value of the initial mass of surface fuel and ash left after burning, and R(m/s) is surface fire spread rate, which can be determined by the ratio

Table 2
Summary of Initiation for Crown Fire from Surface Fire

Case	Crown base height (m)	Moisture content (%)	Tree flowers	Ignition success	Experimental fireline intensity (kJ/(m·s))	Theoretical critical fireline intensity (kJ/(m·s))
01	0.4	45 ± 2	No	Yes	46.49	16.58
02	0.4	55 ± 2	No	Yes	42.05	20.70
03	0.4	65 ± 2	No	Yes	47.34	25.11
04	0.5	45 ± 2	No	Yes	42.01	23.73
05	0.5	55 ± 2	No	Yes	43.83	30.73
06	0.5	65 ± 2	No	Yes	45.93	37.01
07	0.6	65 ± 2	No	Yes	46.64	46.12
08	0.7	65 ± 2	No	No	43.72	60.24
09	0.7	45 ± 2	No	Yes	44.24	39.30
10	0.7	65 ± 2	Yes	Yes	50.86	61.31
11	0.8	45 ± 2	No	No	47.45	50.30
12	0.8	45 ± 2	Yes	Yes	45.48	51.45

of the distance of fire spreading and time required. Figure 4 shows the developments of the temperature above the surface fuel as a function of time. Obviously, the temperature increases slowly for an initial period of time, and then the temperature rises sharply as the surface fire propagates and approaches the measuring point. Using this feature, the start time of the sharp rise is the time when surface fire arrives. In previous work by Liu [27], the moment when the temperature measured by the thermocouples began to undergo a sharp rise corresponds to the time moment for the arrival of flame front at the thermocouple. As seen in Figure 5, the temperature appeared to increase rapidly around 100°C, therefore in this paper 100°C is selected as the characteristic temperature (t_{rea}) when the surface fire is reaching the measuring point. The calculated spread rates of surface fire for different conditions are plotted in Figure 5. It can be found that the surface fire spread rate varies between 0.54 cm/s and 0.75 cm/s. Based on the analysis mentioned above, the critical transition fireline intensity I_0 and surface fire fireline intensity I in the experiments are summarized in Table 2.

It can be seen from Eq. (2) and Table 2, the critical transition fireline intensity I_0 increases with crown base height and moisture content, while surface fire fireline intensity in the experiments I changes between 42.01 kJ/(m·s) and 50.84 kJ/(m·s). Apparently, for the burning experiments without tree flowers, when surface fire fireline intensity I is larger than critical transition fireline intensity I_0, the crown fire can be successfully initiated by surface fire. On the contrary, the crown fire fails to be initiated by surface fire for $I < I_0$. It is worth noting that for the conditions with the existence of tree flowers, the crown fire can be successfully initiated by surface fire even if $I > I_0$. It may be due to that the presence of tree flowers increases the fuel load and makes the tree more flammable, and conse-

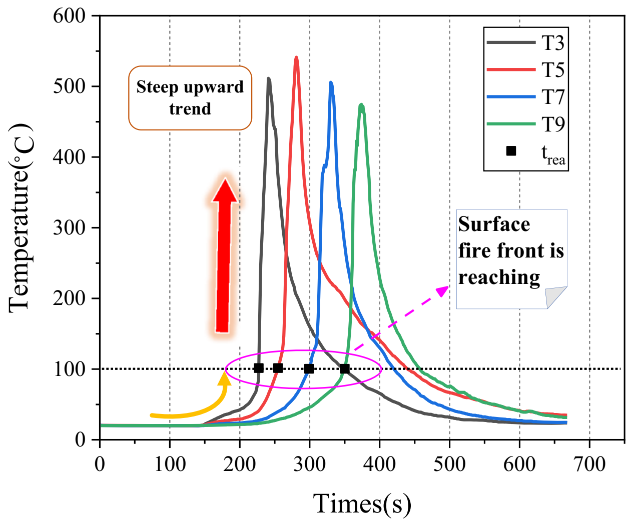


Figure 4. The temperature (t_{rea}) when surface fire reaches the measuring point.

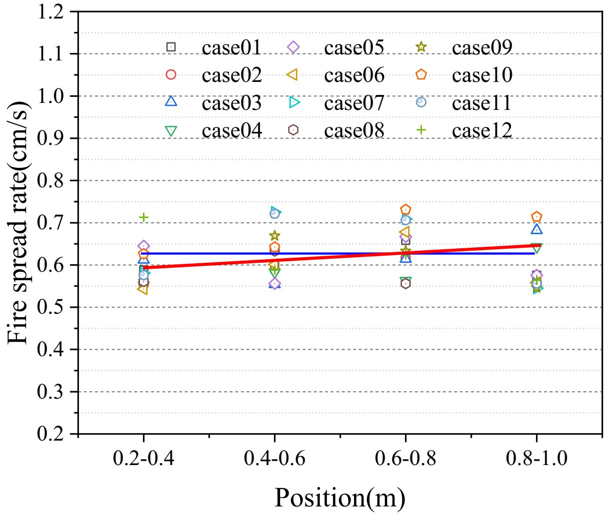


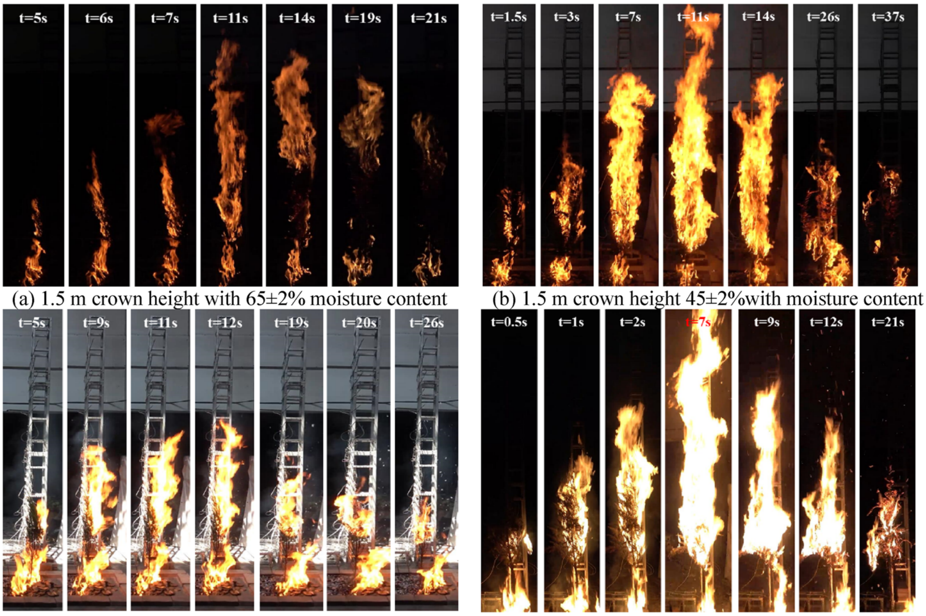
Figure 5. Surface fire spread rate under different experiment conditions.

quently, the crown fires are more likely to occur. It can be summarized that the critical fireline intensity I_0 can be used to determine the initiation of crown fire from surface fire for conditions with the absence of tree flowers, whereas the critical value can not be applied to cases with the existence of tree flowers.

3.2. Effects of Crown Height, Moisture Content, and Tree Flower on Crown Fire Behaviors

3.2.1. Flame Shape Figure 6 represents the ignition, flame spreading, and burning process of crown fire for typical conditions. The flame shape firstly rises to the peak and then declines gradually until the combustion process ends. By comparing Figure 6a, b and c, it can be found that the higher flame height and more intense burning are observed when the tree has lower moisture content and higher crown height. In addition, the flame height and burning intensity are significantly enhanced with the existence of tree flowers.

3.2.2. Flame Height Figure 7 plots the variations of flame height as a function of time for typical conditions. It can be found that the flame height increases first, reaches the maximum value, and then decreases until the crown extinguishes. From Figure 7a and b, as the moisture content increases, the maximum flame height decreases, but the required time of flame height reaching the maximum value is delayed. This is mainly due to that the greater the moisture content of the crown, the greater the amount of heat consumed by water vaporization. As the crown height increases from 1.0 m to 1.5 m, the flame height increases significantly, and the required time of flame height reaching the maximum value is reduced. In addition, for fixed moisture content and crown height conditions, the



(a) 1.5 m crown height with 65±2% moisture content

(b) 1.5 m crown height 45±2%with moisture content

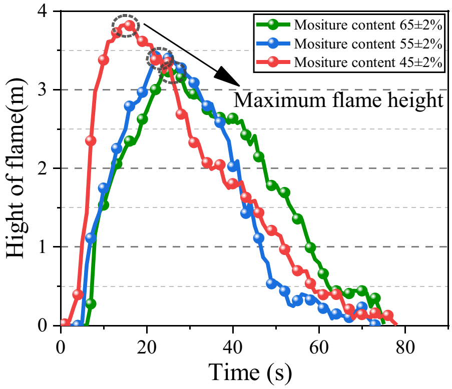
(c) 1.0 m crown height with 45±2% moisture content

(d) 1.5 m crown height covering with tree flowers with 45±2% moisture content

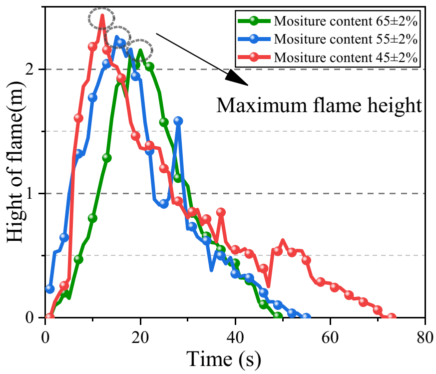
Figure 6. Flame shape under different experiment condition.

maximum flame height increases when the tree is covered by tree flowers. The maximum flame heights for different conditions are described in Table 3. It is noted that the lower the moisture content and the higher the crown, the greater the maximum flame height of the crown fire. Notably, the existence of the tree flowers can also increase the maximum flame height of the crown fire and consequently increase the risk of crown fire.

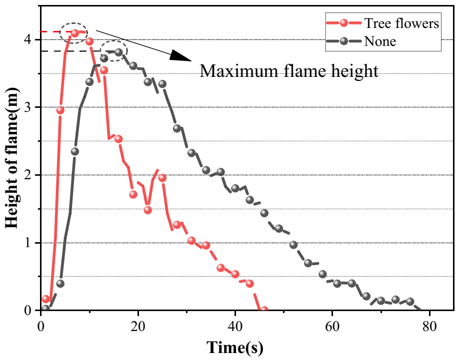
3.2.3. Fire Plume Temperature Figure 8 plots the variations of fire plume temperature as a function of time under different experimental conditions. Six measuring points, which are labeled by 01–02 (crown base height), 03–04 (middle of the crown) and 05–06 (top of the crown), are selected to compare the crown fire temperature of different heights. Obviously, the crown fire temperature rises sharply to the peak and then drops until the temperature reaches the ambient temperature. It is worth noting that the maximum temperature appeared at the middle of the crown, whereas the minimum temperature is observed at the crown base. The maximum fire plume temperature for different conditions are described in Table 3. It can be noted that the higher crown height and lower moisture content are, the maximum fire plume temperature seems to be lager. When the height of the crown is higher, the more combustible material there is and the more combustible gases are produced by pyrolysis. Therefore, the higher the crown height, the larger the maximum flame plume temperature. Meanwhile, the tree species covered with tree



(a) 1.5 m crown height with different moisture contents



(b) 1.0 m crown height with different moisture contents



(c) 1.5 m crown height with absence of and existence of tree flowers with 45±2%moisture content

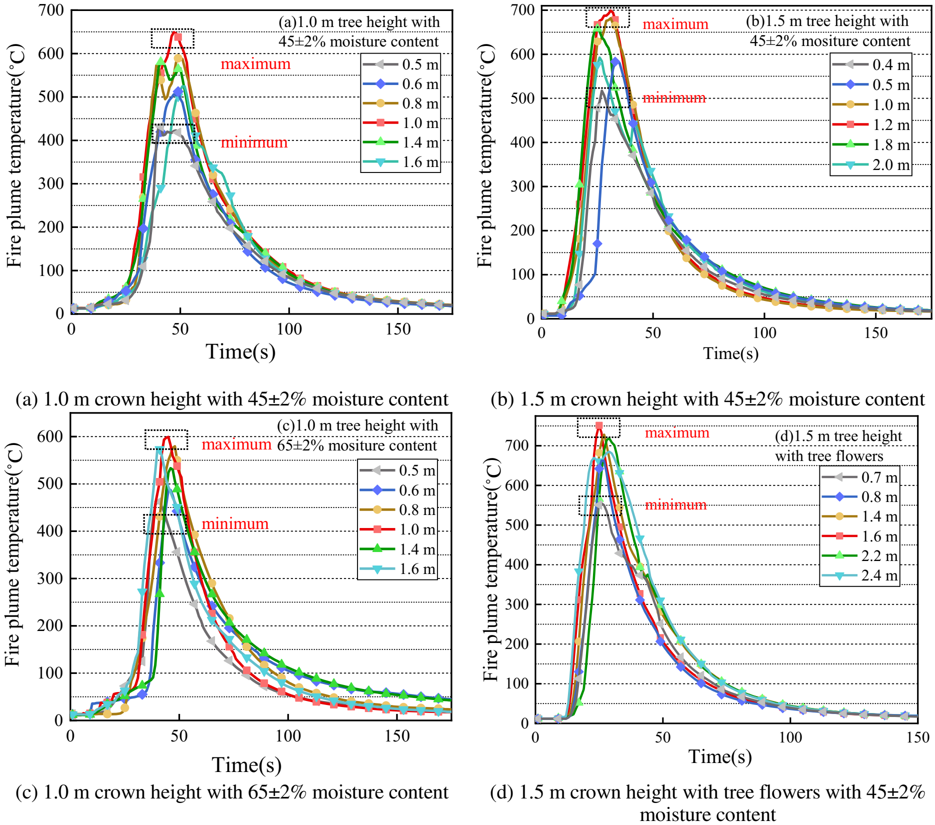
Figure 7. Time evolution of flame height with different experiment conditions.

flowers have a larger fire plume temperature owing to the increased fuel load and flammability.

3.2.4. Radiant Heat Flux Figure 9 shows the variations of radiant heat flux as a function of time for typical conditions. It can be found that the radiation heat flux of each measuring point increases rapidly to the maximum value and then gradually decreases to the initial state. Apparently, the maximum values of radiation heat flux appear at the middle of the crown for different experimental conditions. The maximum flame radiation heat fluxes for different conditions are described in Table 3. It can be seen that as the moisture content changes from low to high or the crown height decreases, the maximum value of radiation heat flux shows a decreasing trend. For example, the maximum radiation heat flux in cases of 1.5 m crown height with 45 ± 2% moisture content is 13.48 kW/m^2, whereas the corresponding value for cases of 1.5 m crown height with 65 ± 2% moisture

Table 3
Summary of Maximum Flame Height, Fire Plume Temperature and Radiant Heat Flux

Experimental conditions	Maximum flame height (m)	Maximum fire plume temperature (°C)	Maximum radiant heat flux (kW/m^2)
case01	3.82	699.0	12.59
case02	3.42	670.1	10.76
case03	3.26	645.8	8.56
case04	2.44	649.1	10.59
case05	2.27	632.2	8.13
case06	2.16	599.2	7.30
case12	4.10	753.1	18.55



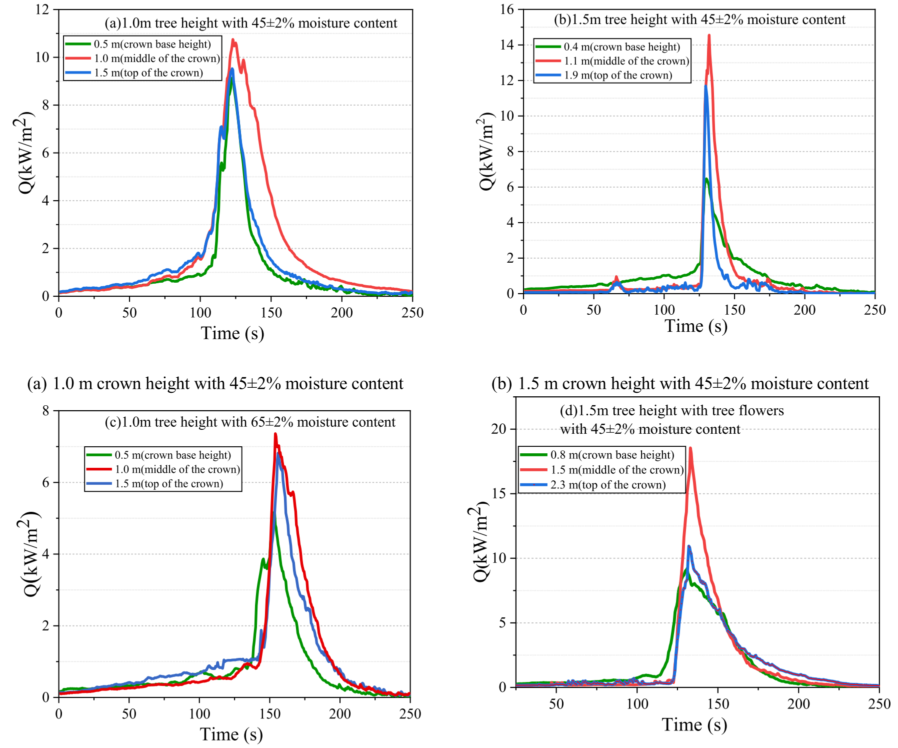
(a) 1.0 m crown height with 45±2% moisture content

(b) 1.5 m crown height with 45±2% moisture content

(c) 1.0 m crown height with 65±2% moisture content

(d) 1.5 m crown height with tree flowers with 45±2% moisture content

Figure 8. Time evolution of fire plume temperature under different experimental conditions.



(a) 1.0 m crown height with 45±2% moisture content

(b) 1.5 m crown height with 45±2% moisture content

(c) 1.0 m crown height with 65±2% moisture content

(d) 1.5 m crown height with tree flowers with 45±2% moisture content

Figure 9. Time evolution of radiant heat flux change under different experimental conditions.

content is 8.65 kW/m^2. Besides, the maximum values of radiation heat flux for cases with the existence of tree flowers is significantly larger than that for cases without tree flowers, which indicates that the tree species with tree flowers burn more intensely and produces more combustion heat.

4. Summary and Conclusion

This paper carries out a series of comparative experiments using real tree species to investigate the initiation conditions and burning behaviors of crown fire, taking crown height, crown moisture content and tree flowers into account. The main valuable conclusions have been drawn: The higher crown base height and the larger moisture content are, the crown fire initiation success from surface fire decreases, while the existence of tree flowers tends to lead to initiation success of crown fire. The critical fireline intensity can be used to determine the initiation of crown fire from surface fire for conditions with the absence of tree flowers, whereas the critical value can not be applied to cases with the existence of tree flowers. When the tree has lower moisture content and higher crown height, the maximum values of the flame height, fire plume temperature, and radiation heat flux of crown fire are larger. Moreover, when the tree is covered with tree flowers, the flame height, fire plume temperature, and radiation heat flux of crown fire increase significantly due to the increases in fuel load and flammability. In this paper, only 12 experiments were conducted to investigate the effect of two different crown heights with three different moisture contents and the presence or absence of tree flowers on crown fire, therefore only qualitative analysis of initiation conditions and burning behaviors of crown fire were conducted, but the quantitative theoretical analysis had some limitations. The burning experiments with various crown heights and different tree flower arrangements will be carried out further to investigate initiation conditions and behaviors of crown fire, and the quantitative and theoretical analysis will be performed to predict the crown fire behavior.

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