Experimental study on catastrophe characteristics of forest fire spread*

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Abstract The dynamical behavior of forest fire in different slope grades were observed in the experiment of simulating the forest fire propagation using fuel-bed. The experiment has shown that the catastrophe of the forest fire spread is related to the slope grade of the forest area.

Keywords: forest fire, slope grade, state change, catastrophe.

China has a vast expanse of upland, and most of the forests are distributed in mountainous areas. So the study on forest fires of mountains is very important. The forest fire is divided into surface fire, crown fire, fly fire and fire whirl and so on. It is shown by statistical results that the surface fires amount to 90% of the forest fires. The surface fire can easily induce crown fires, thus enlarging fire risk. There are many uncertain factors which cause forest fires in mountain area. Fully understanding the status and trends of fire fields, mastering forest fire characteristics in different mountain landforms, especially in woodlands with varied slope grades will be helpful to prevent and suppress forest fires. The study of surface fire is an important content in the investigation of dynamical characteristics of forest fires.

In ref. [1] many numerical simulations and statistics analysis were conducted. It has been found that the relation between the numbers of fires per time step and the burned area in each fire is fractal. The numerical fractal dimension derived from model data is 1.02—1.18, but the fractal dimension derived from the practical data is 1.31—1.49. The difference comes from the environment and human-related variables that affect the size of wildfires, the proximity and type of combustible materials, meteorological condition, and the efforts of fire prevention. By the studies of the dynamical characteristics and statistics analysis of forest fires, many valuable results have been achieved[2,3].

In this paper, catastrophe, a nonlinear characteristic of forest fire, will be analyzed based on the experiments of forest fire spread, and the behavior of fire sudden jump will be described with catastrophe theory[4,5].

1 Experimental

The experimental equipment for the study of woodland forest fire with different slopes consisted

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of main fuel bed, extending fuel bed, obliquity changing instrumentation, ignition system, camera system, thermocouples and recording instrument. The main fuel bed (see fig. 1) was the core of the whole facility, which ensured the combustion line long and wide enough for the observation and measurement of fire spread. The bottom of fuel bed was made of 4 layers of gypsum with 0.01 m thickness, and the heating conductivity of gypsum was equivalent to that of clay. The baffle in each side of fuel bed was made of adiabatic material with 0.01 m in thickness and 0.30 m in height in order to avoid rolling flow and to obtain a uniform height of combustibles in fuel bed. The fuel bed was fixed in a rotatable supporting frame. When the angle of supporting frame was changed, the woodlands with different slopes could be simulated. The ignition system consisted of line ignition instruction, spark plug, rising press circuit and liquefied petroleum gas (LPG) bottle. The photo system was used to record the typical phenomena and spread process of surface fire, and to provide reference velocity for the fire spread when the fuel bed was placed flat or with a small angle on the supporter, and to be one of important measurement references of flame height. A series of thermocouples were embedded into the floor of fuel bed with an interval of 0.4 m between two thermocouples. This interval could not only reduce the error of measurement delay, which might occur if the interval was too small while the fire spread was fast, but also avoid wasting too much time due to slow combustion at a small slope grade. The thermocouples stretched out the floor of fuel bed for a height of 0.18 m which was higher than the combustible layer. Although the highest temperature of flame in slow combustion could not be measured, the measured temperatures could be close to the highest one when the flame was kept close to the floor of fuel bed. In order to observe the flame changing from flat to slope, and to compare the fire characteristics in these two cases, an extending fuel bed with a length of 1.5 m was built. Its other structural parameters were the same as those of the main fuel bed. The experimental equipment is shown in fig. 2. Pine needles were as combustible in experiments, and the thickness, weight and types in the extending bed were the same as those in main fuel bed.

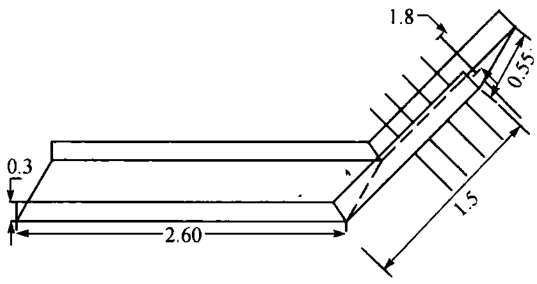

Fig. 1. Schema of main fuel bed, extending fuel bed and thermocouples.

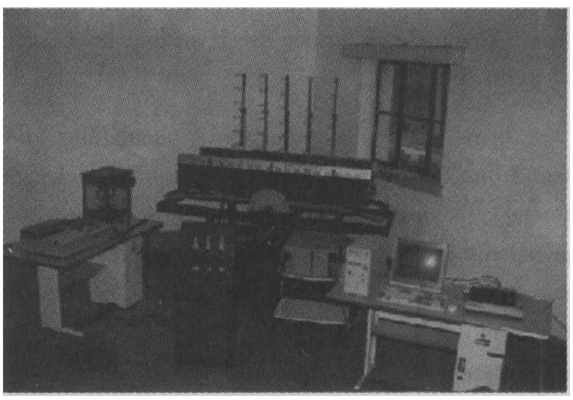

Fig. 2. Experimental apparatus of forest fire spread.

2 Analysis on characteristics of forest fire

Using the experimental apparatus described above, the flame height and fire spread velocity in different slopes were measured. Figs. 3(a) and (b) are the flame on flat and slope. The measurement results of the changes of fire spread and flame height in different slopes are shown as figs. 4(a) and (b). The timing started from the moment when the combustion flame became approximately stable after the fuel in main fuel bed was ignited. In order to analyze the dynamical characteristics of forest fire in different slopes, the tested results are drawn in the same coordinate system. The related parameters of forest fire spread experiments are listed in table 1.

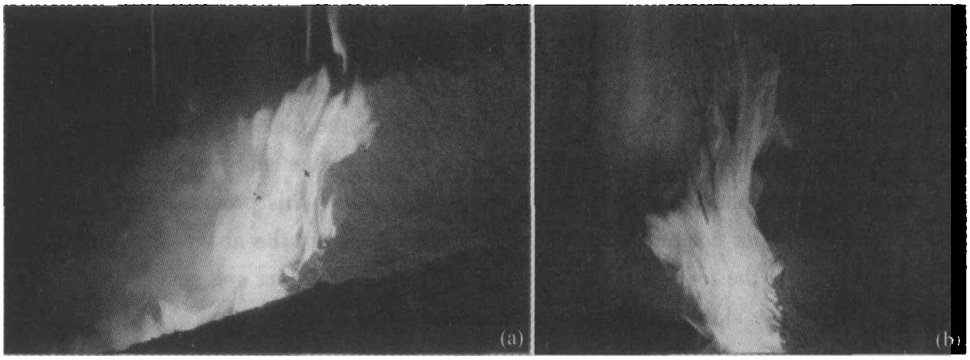

Fig. 3. Flame in different slopes. (a) Slope woodland; (b) flat woodland.

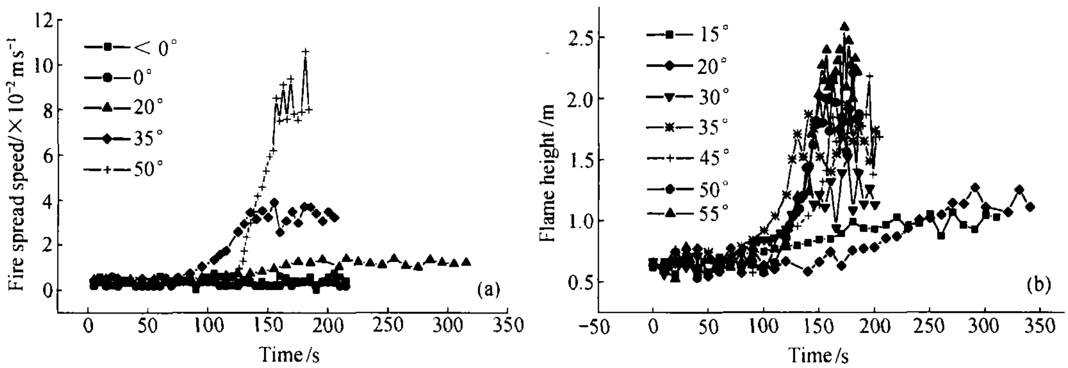

Fig. 4. Change of the fire spread speed and flame height with time in different slopes. (a) Fire spread speed; (b) flame height.

Table 1 Related parameters of forest fire spread experiments

Nomuber	Placed angle of fuel bed/(°)	Weight of combustibles/kgm^{-2}	Thickness of combustibles/m	Environment temperature/℃	Air relative humidity/%
1	< 0	2.02			88
2	0	2.02			88
3	20	1.762	0.14	17.0	90
4	35	1.462	0.13	17.5	90
5	50	1.758	0.13	17.5	90

According to figs. 4(a) and (b), the following results have been obtained.

(i) When the woodland slope was less than 20°, with the increase of slope, the changes of the flame height and fire spread speed in main fuel and extending fuel beds were smooth. The flame was of a small fluctuation and presented stable combustion within small slope range, and flame inclined towards baffles in some sort.

(ii) When the slope was larger than 20°, in the initial combustion stage, the flame height and fire spread speed were comparatively stable and fluctuations was not too large. With the development of combustion, fire varied from stable combustion to dithering combustion. When the slope was 35°, the jumps of flame height and fire spread speed were 0.97 m and 0.028 m/s respectively. In the dithering combustion stage, the combustion was attached to the wall of fuel bed. In the meantime the fire spread speed and fire height dithered around their balance values, and their fluctuation scopes were 0.009 m/s and ± 0.25 m respectively. The reason of fluctuations of flame height and fire spread is that the flame is attached to the wall of fuel bed and the fuel combusts rapidly as a result of whirl, but soon there is not enough air so the flame becomes smaller and leaves the wall of fuel bed. Afterward the flame gets enough air and combusts rapidly again. This process repeated again and again so as to form dithering combustion. It can be concluded from the above analysis that when the slope is larger than 20°, the forest fire characteristics will transfer from one steady state (stable combustion) to another steady state (dithering combustion).

(iii) When the slope was larger than 50°, the combustion process transfers between two kinds of combustion: stable combustion and dithering combustion, but the transferring time was much shorter and the jumps of flame characteristics became larger. The jumps of fire height and fire spread speed were 1.8 m and 0.085 m/s respectively. With the increase of slope, the fluctuation ranges of flame height and fire spread speed extended, but dithering period became shorter. When the slope was 50°, the dithering scopes of flame height and fire spread speed were ± 0.45 m and 0.25 m/s respectively.

3 Cusp catastrophe analysis on forest fire characteristics

The unstable characteristics of forest fire in different slopes as described above can be analyzed using a cusp catastrophe model. The cusp catastrophe model has two control variables and one state variable. Here, the woodland slope M and the combustion progress H are taken for the control variables, and the forest fire characteristics F is taken as the state variable. The cusp catastrophe model of forest fire characteristics is shown in fig. 5. The top surface of manifold denotes the steady state of stable combustion with small combustion fluctuation. However, undersurface of the manifold denotes the steady state of dithering combustion with great fluctuation in combustion characteristics. The change from the top surface to the undersurface represents the process that combustion transfers from one steady state to another. The forest fire characteristics F may change with the change of M and H. For the curves $a_ib_ic_id_i$ ($i = 1,2$) shown in fig. 5, $b_i \to c_i$ ($i = 1,2$) represent the sudden jumps of state variable F, and the jump values are $\Delta F = F(H_{b_i}, M_{b_i}) - F(H_{c_i}, M_{c_i})$ ($i = 1,2$). Their projects on the bifurcation are the curves which cross the edge of bifurcation. When the slope increases to a certain value, for different M, the jump of F is different although the change process of H is the same. For the combustion process $a_1b_1c_1d_1$, the jump $\Delta F_1 = F(H_{b_1}, M_{b_1}) - F(H_{c_1}, M_{c_1})$, but for $a_2b_2c_2d_2$ $\Delta F_2 = F(H_{b_2}, M_{b_2}) - F(H_{c_2}, M_{c_2})$. Ob-

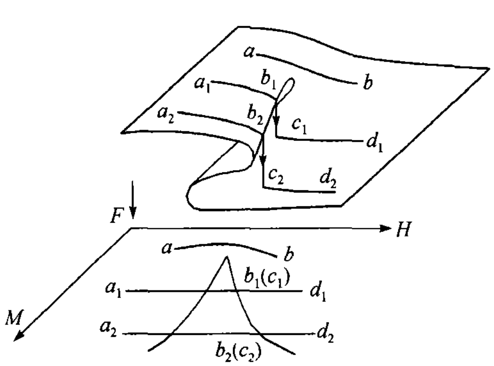

Fig. 5. Description of cusp catastrophe of forest fire characteristics.

viously, $\Delta F_1 < \Delta F_2$, and they cross over bifurcation by different paths. If combustion process, such as curve ab, does not cross over the bifurcation, i.e. the slope is small or fuel bed inclines downwards, the combustion process becomes relatively steady. In this case, the forest fire can be easily controlled. But for steep slope, the jump of forest fire characteristics increases, so the fire is difficult to be controlled. The above analyses are generally in agreement with the experimental results.

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