A Study of Fire Spread Along the Surface Fuels on the Ground

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An experimental apparatus is specially designed for studying the law of the fire spread along surface fuels on the ground in forest. By using the apparatus, the factors such as fuel load, packing ratio, etc., can conveniently be controlled for analysing the influence of them on the fire spread. A great deal of experiments have shown that the fire spreading speed will consequently increase when the fuel load rises, and gradually increase when the packing ratio of the fuel increases. Through observing the phenomenon during experiments, the nature of how the factors influent the fire spreading speed has been discussed.

Based on the concept of fire intensity, a semi-experiential estimated equation related to fuel load, packing ratio, and other parameters was set up. According to some parameter's values measured by experiments, the values of flame spreading speeds could be calculated, the calculated results are approach to the values measured during experiments.

I. Introduction

In forest fires, the surface fires on the ground occur very frequently, and hold above ninety percent of the forest fires. Almost all the fires in forest are brought about by them. So, it has a great significance to study the law of flame spread in surface fires for revealing the internal cause of the occurrence and development of forest fires.

The spread of surface fires on the ground is restricted by some factors, such as the composition of the surface fuels, fuel load, packing ratio, moisture, conditions of topography and weather, etc.. Among these factors, the fuel load and packing ratio are all important factors, and the varying of them changes the intensity and spreading speed of the forest fire remarkably[1]. Many foreign scholar touched upon the effect of fuel load and packing ratio in their research of the forest fire, but they couldn't reveal the mechanisms of the effect and the essential relation of them[2] indeed. Therefore, the authors have designed a set of experimental apparatus for the special study of the action of fuel load and packing ratio. By measuring the heat transfer from the flame to the unburnt part, the reason how the fuel load and packing ratio changes fire spreading speed has been discussed. In addition, a convenient estimated method has been advanced according to the experimental results, which can be used for calculating the flame spreading speed by using some values of parameters measured by experiments. At last, the method has been applied to some experimental examples.

II. Experimental Method

The experimental apparatus which designed to simulate the spread of surface fires in the forest is shown in Fig.1.

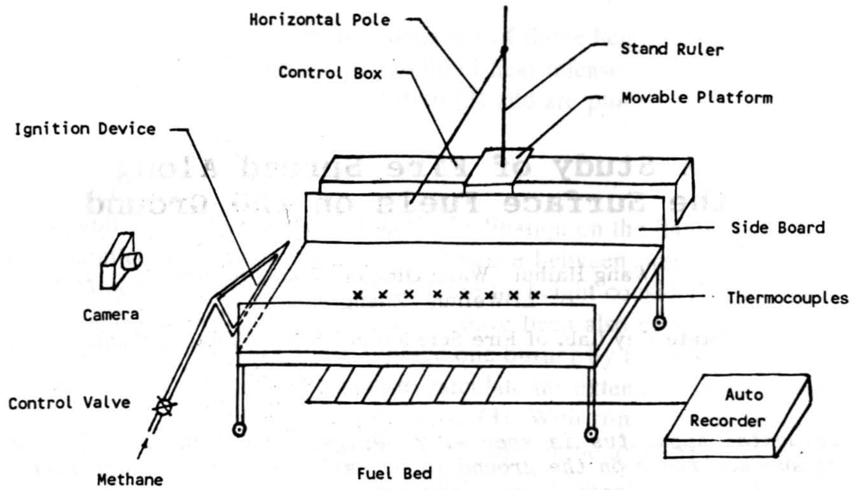


Fig.1 The schematic drawing of experimental apparatus.

(1) Fuel Bed

It is used to lay tiny combustible materials with a certain fuel load. The fuel bed is 200 cm long and 52 cm wide. To simulate dry soil ground, the bed surface is made of prefabricated board whose thermal property is similar to the dry soil's. On each side of the bed there is a vertical board which is along with the direction of length. The height of board is 35 cm which is a average height of the steady fire and can prevent the wind flow. Outside the adiabatic materials are pasted on the inside wall of board to produce the condition of adiabatic wall to ensure that fire is similar to the wild Land fire.

(2) Temperature Measuring System

It is composed of a group of NiCr-NiSi thermocouples and a auto balance recorder. The thermocouples are arranged on the surface of fuel at a constant distance (along the middle line of the bed) to record the change of temperature at different position of the fuel surface during flame spread.

(3) The flame height measuring device

The flame height is determined by the position where the flame appears at the probability of 50%. The flame height measuring device is composed of a movable platform, stand rule, horizontal pole and control box. The movable platform has the function of tracing the flame front automatically ,the rising and dropping of horizontal pole can be controlled and the stand rule is used to record the height of flame.

During the experiment, the fuel with the definite moisture is arranged evenly on the bed, the fuel load can be controlled by changing the quality of fuel and also the packing ratio is adjusted artificially. After being ignited by the igniting device, the temperature measuring device is switched on to monitor the temperature of the spots on fuel surface at a constant distance apart. The flame spreading speed (S_f) of different part can be gotten by dealing with the temperature curves. Generally, the flame spreading speeds in different parts are fluctuated, therefore, it is necessary to make average of flame spreading speed in different parts in order to get representative value of spreading speed which is expressed as $\overline{S_f}$. The flame height (H_f) can be gotten from the flame height measuring device and it is also the average of flame height of different part.

The typical phenomenon of experiment is recorded by camera and it is also possible to verify the flame height by the photos. After combustion, the remnant ashes is weighted.

The fuel in the experiment is mainly: the long length grass with the length of 60~80 cm, the middle length grass with the length of 40~60 cm, the short length grass with the length of less than 40 cm and the parasol leaves. The moisture of the fuel is adjusted by heating the fuel to different level.

III. Experimental Results and Analyses

1. The foundmental process of flame spread

After ignition, the flame emerges above the combustible materials on the ground. The fuel participating in the chemical reaction the flame area comes from the combustible volatiles of the thermal decomposition of surface fuels. In fact, the process of the flame spread toward the unburnt part is the one which the flame ignites the unburnt fuel nearby continuously[3] through heating the unburnt part. When the temperature rises to a critical value, the unburnt part begins to decompose and produces volatiles. When the combustible volatiles accumulates to a certain concentration, the flame will spreads to this position[4]. (See Fig.2)

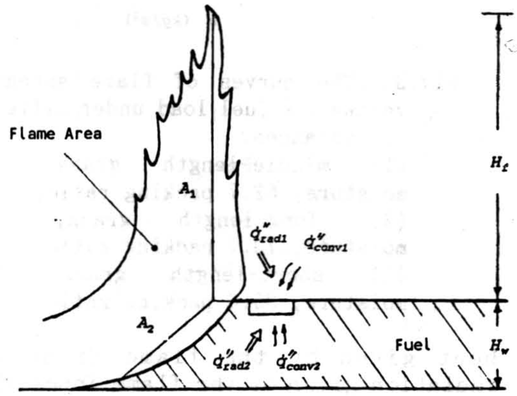


Fig.2 The schematic drawing of flame advancing process along the fuels layer and the heat transfer between the flame and unburnt part of the fuels.

Because the surface fuel on the ground is composed of tiny combustible meterials, the flame not only propagates along the surface, but also spreads deep into the fuels. The flame inside the fuels move forward with a parabolic flame front (See Fig.3), and the flame on the surface of the fuels is at the most front. So the spreading speed of the flame on the surface indicates the advancing speed of the flame.

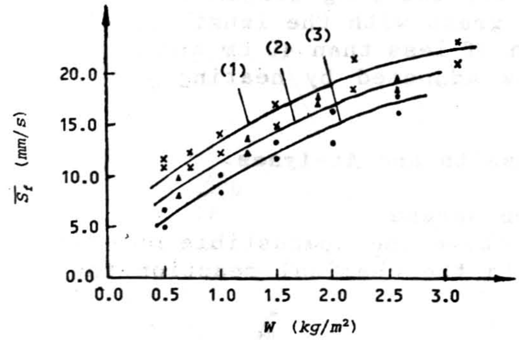
2. The influence of the fuel load on flame spread

With the same moisture and packing ratio, the experiments show that when the fuel load increases, the flame spreading speed tends to increase. (Fig.3).

The experiments also shows that the height of the flame varys with the change of the fuel load. Fig.4 shows the tendency of the change of flame height versus fuel load in three different circumstances. When the fuel load increases, the height of flame rises, too.

Under the conditions that other parameters keep constant, the increase of the fuel load leads to the increase of fuel which participates the thermal decomposition per unit area. And when only fuel load varys, the composition and concentration of the volatiles keep nearly the same, and the reaction velosity of the volatiles in flame area above surface fuels is also nearly the same. This makes the flame area expand with the increase of the quality of the volatiles per unit area, and so the height of flame rises under the effect of natural convection.

On the surface of fuel layer, the flame continuously ignites the unburnt fuel nearby, which leads to the advance of flame. The heat absorbed by the unburnt part nearby is mainly composed of the radiation



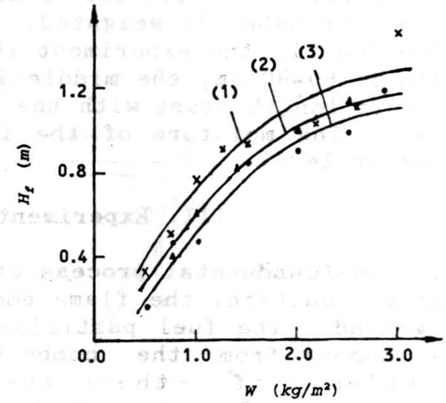


Fig.3 The curves of flame spreading versus the fuel load under different cirumstances.
(1) middle-length grass, 2.4% moisture, 52.7 packing ratio;
(2) long-length grass, 4.0% moisture, 72.7 packing ratio;
(3) short-length grass, 8.0% moisture, 35.6 packing ratio.

Fig.4 The curves of flame heights vs the fuel load under different circumstances.
(1) middle-length grass, 2.4% moisture, 52.7 packing ratio;
(2) long-length grass, 4.0% moisture, 72.7 packing ratio;
(3) short-length grass, 8.0% moisture, 35.6 packing ratio.

heat given by the flame front over the fuel surface $\dot{q}_{rad1}$, the heat radiation given by the flame inner the fuels $\dot{q}_{rad2}$ and the heat convection $\dot{q}_{conv}$ which is given by the heat air nearby. Assuming that Q_{ig} is the heat which per unit fuel need being ignited, the relation between the spreading speed $\overline{S_f}$ and the heat being absorbed by the unburnt part is given as follows[3][5]:

$$\overline{S_f} = \frac{\dot{q}_{rad1}+\dot{q}_{rad2}+\dot{q}_{conv}}{\rho_b \cdot ds \cdot \tau \cdot Q_{ig}} \tag{1}$$

here ρ_b is bulk density, β is packing ratio, ds is the surface area of unburnt part, τ is the thickness of unburnt fuel layer.

To a certain kind of grass,if the moisture is kept constant and only the fuel load is varying, then the product term in denominator of the right side is kept constant.

With the rise of fuel load, $\dot{q}_{rad1}$ and $\dot{q}_{rad2}$ will increases because H_f and H_w increases; but while keeping the other conditions fixed, $\dot{q}_{conv}$ will not change much relatively. When fuel load increases, the flame spreading speed will increases also according to Eq.(1).

3. The influence of packing ratio on flame spread.

The distribution of the combustible materials on the ground can be measured by packing ratio. Packing ratio refers to the ratio of volume the fuel occupies to the volume of the fuel itself in a specific volume. It may be described as

$$\beta \doteq \frac{\rho_f}{\rho_b} = \frac{\rho_f}{w/b} \tag{2}$$

here ρ_f is the density of fuel itself. ρ_b is the bulk density. In the equation, $\rho_f \gg \rho_b$ is used.

Additionally, the relative packing ratio is defined as:

$$\beta_b/\beta_{10}' = \frac{b}{10} \qquad (3)$$

here b means the thickness of the fuel layer.

Fig.(5) is the curves of fire spreading speeds versus packing ratios by experiments. The curves indicate that the varying of packing ratio has much effect on the fire spreading speed. The speed may increase with the rise of packing ratio. When the packing ratio decreases to a critical value, the flame will even no longer be able to propagate along the fuel layer any more.

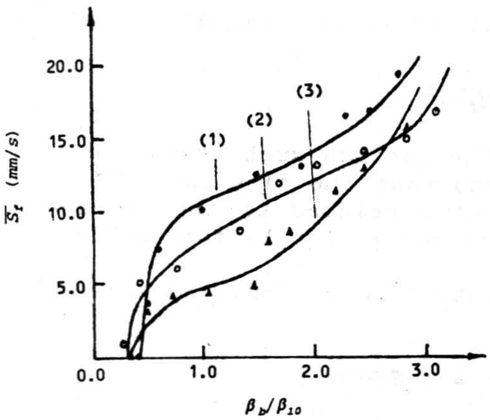


Fig.5 The curves of spreading speeds versus the packing ratio under different circumstances.
(1) long-length grass, 1.4 kg/m^2 fuel load, 3.5% moisture;
(2) middle-length grass, 1.0 kg/m^2 fuel load, 14.4% moisture;
(3) fallen leaves, 0.75 kg/m^2 fuel load, 7.1% moisture.

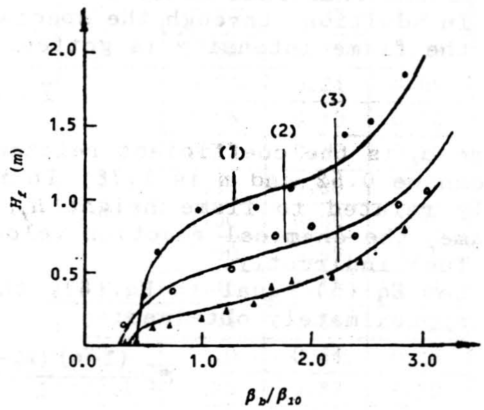


Fig.6 The curves of flame height vs the packing ratio under different circustances.
(1) long-length grass, 1.4 kg/m^2 fuel load, 3.5% moisture;
(2) middle-length grass, 1.0 kg/m^2 fuel load, 14.4% moisture;
(3) fallen leaves, 0.75 kg/m^2 fuel load, 7.1% moisture.

It is found that the flame height increases with the rise of packing ratio. (Fig.6). The rise of packing ratio will lead to the increase of penetrating depth of external flame's radiation inside the fuel layer, and it will also strengthen the radiation efficiency of internal flame to the unburnt part. In addition, the improvement of the degree of porosity also strengthen the partial convection heat transfer inside the fuel layer. All these leads to the increase of velocity of the combustible volatiles from the thermal decomposition of fuel layer, therefor, the height of flame rises.

From Eq.(1) with the increase of packing ratio, $\dot{q}_{rad1}'$ will increase for H_f increases; with the improvement of the porosity of fuel, the radiation that micro-area absorbs from the internal flame will increase, too. In addition, because of the distinct increase of $\dot{q}_{conv}''$, the flame spreading speed increases.

IV. Semi-experiential estimated equation

According to the concept of fire intensity, the formula of instantaneous fire intensity is given as:

$$I = -\frac{d}{dt}[(1-\eta)\cdot w]\cdot Q_i \tag{4}$$

here η is moisture, Q_i is the quantity of heat released from a unit mass of fuel, expressed as the product of q_i (calorific value of unit mass fuel) and $(1+\beta)^k$ (the revising part)

Making substitute and integrating it with x, so

$$\overline{I} = \frac{(1-\eta)(W_0-W_k)}{L}\cdot\overline{S_f}\cdot(1+\beta)^r\cdot q_i \tag{5}$$

where L is the distance the flame passed by, W_0 is the initial fuel load, W_k is the fuel load after combustion.

In addition, through the special study of flame intensity, the formula of the flame intensity is gotten as:

$$\overline{I} = c_1\cdot\beta^s\cdot H_f^m\cdot\delta_f^n \tag{6}$$

here c_1 is the coefficient related to the factors such as moisture etc., m can be 0.52 and n is 1.76. It is found that the fire intensity is not only related to flame height H_f, but also related to the thickness of flame, the chemical reaction velocity is controlled by the packing ratio of fuel indirectly.

Let Eq.(5) equal to Eq.(6), the equation about flame spreading speed is approximately obtained:

$$\overline{S_f}\cdot\frac{(1-\eta)(W_0-W_k)}{L}\cdot q_i = c_1\cdot\beta^k\cdot H_f^m\cdot\delta_f^n \tag{7}$$

here $k=s-r$, its value is 0.04.

After determining the concerned parameters under a certain circumstance, Eq.(7) can be used for calculating the flame spreading speed. The concerned parameters' values from the experiments of several kinds of combustible materials are listed in Tab.(1). The comparison between the experimental curves and the calculated results are shown in Fig.(7). Fig.(7) indicates that the calculated results coincide with the experimental results and it is identified that the method is feasible and effective.

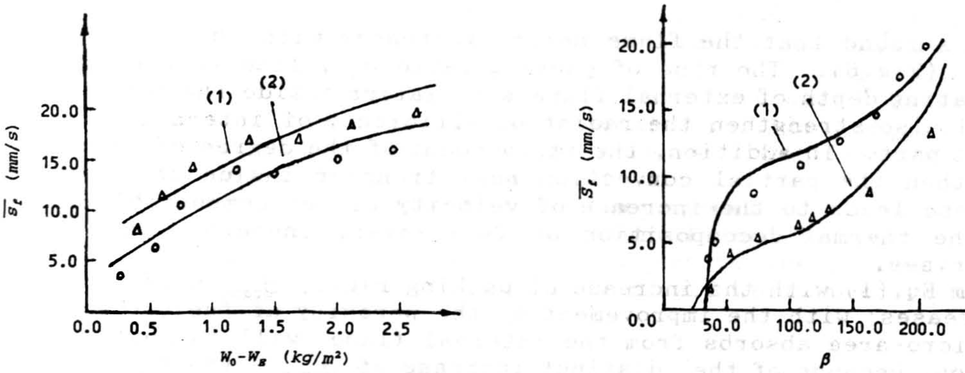


Fig.7 The comparisons between calculated results and experimental results. (a): (1) middle-length grass, 2.4% moisture, 52.7 packing ratio; (2) short-length grass, 8.0% moisture, 35.6 packing ratio; (b): (1) long-length grass, 1.4 kg/m^2 fuel load, 3.5% moisture; (2) fallen leaves, 0.75 kg/m^2 fuel load, 7.1% moisture.

Tab.1 The values of the parameters measured by experiment.

surface fuels	C_1	q_i (kcal/kg)	η (%)	β	W_0-W_k (kg/m²)	H_f (m)	δ_f (m)
middle-length grass	289.5	4234.1	2.4	52.7	0.40	0.35	0.15
					0.60	0.53	0.20
					0.85	0.80	0.25
					1.30	0.96	0.32
					1.70	1.11	0.35
					2.13	1.37	0.40
					2.65	1.44	0.43
short-length grass	275.1	4240.7	8.0	35.6	0.27	0.24	0.09
					0.55	0.43	0.16
					0.73	0.47	0.22
					1.20	0.80	0.30
					1.50	0.90	0.32
					2.00	0.99	0.38
					2.45	1.18	0.41
long-length grass	331.9	4226.5	3.5	19.5	0.95	0.34	0.13
				23.4	1.10	0.64	0.18
				39.1	1.15	0.83	0.20
				58.6	1.20	0.85	0.24
				72.7	1.22	0.94	0.25
				89.9	1.28	1.36	0.25
				97.7	1.28	1.50	0.26
				109.0	1.28	1.69	0.27
fallen leaves	356.6	4309.6	7.1	37.9	0.50	0.13	0.09
				53.1	0.63	0.14	0.10
				75.9	0.66	0.19	0.11
				110.0	0.66	0.27	0.12
				121.0	0.66	0.38	0.15
				136.6	0.66	0.40	0.17
				166.9	0.66	0.48	0.17
				212.4	0.66	0.77	0.19

V. Conclusions

The experimental apparatus, which is special designed for studying the surface fires on the ground, can adjust the conditions of all aspects conveniently, and study the influence of fuel load and packing ratio on fire spreading speed.

The experimental results show that: while keeping other conditions fixed, the flame spreading speed $\overline{S_f}$ will increase with the rise of fuel load W. When the fuel load increases, the flame height rises, too, which leads to the increase of radiation heat flux to the unburnt part, and makes the flame spreading speed faster.

The fire spreading speed will increase while the packing ratio of fuel increases. The increase of packing ratio strengthens the radiation action of the flame to the fuel layer of unburnt part, and intensifies the convective heat transfer inside the fuel layer, which leads to the increase of the velocity of thermal decomposition, the intensity of fire and the fire spreading speed.

Using the semi-experiential equation of fire spreading speed which bases on the concept of fire intensity, the fire spreading speed can be calculated according to some parameters, and the calculated results coincides with reality. Even though there are many parameters to be measured, the method has much practical value, and it makes a step for setting up a accurate fire propagation model which is fit for the necessity of engineering.

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