DUAL-NATURE CHARACTER OF FIRE RULES AND ITS APPLICATION

Chen Li, Fan Weicheng
(State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui 230026)

ABSTRACT

Fire rules have dual nature character: deterministic nature and probabiliatic nature. Only when we study not only its deterministic nature but also its probabilistic nature and furthermore study their combination, can we understand the rules of fire as a whole.

The academic thought of dual-nature character of fire rules has been put forward in this article, and the concrete method of its application to demonstrate fire process has been clarified by constructing a deterministic and probabilistic model for room fires. A great quantity of calculation on computer shows, this model can predict conveniently whether a room fire will do harm to persons on the spot and the probability of this harm at a certain time.

1.INTRODUCTION

There are rules for fire occurring, growing and fire protecting. These rules, however, are neither totally deterministic nor totally probabilistic. They have both deterministic and probabilistic characters. Only when we investigate the deterministic nature and the probabilistic nature and their combination can we understand the rules of fire as a whole. The dual nature character of fire rules could be demonstrated by taking the fire occurrence as an example. If the combustible objects, environment conditions are given, it can be determined whether a specific fire source can cause a fire with the advanced scientific experiment and computer modelling. However, as a hazard, fire always covers a wide range to some extent. The human behaviour, the variety of combustible objects, environment conditions and fire source, etc, inevitably give rise to the probabilistic nature of fire occurring which makes it undeterminable to predict definitely whether or when or where the fire will occur. Thus, the reasonable goal of investigation is to provide the probabilistic nature of fire occurring and its connections to various factors. Just as the fire occurring, fire growing and fire risk also have both deterministic and probabilistic character.

The prime method to study the deterministic nature of fire is modelling research, and the main method to investigate the probabilistic nature is statistic analysis. The modelling methods, composed of experimental modelling and computational modelling, are various and so do the models applied in statistic analysis. The purpose of this paper is not to review the existing modelling and statistic methods, but to try to propose a kind of theoretical framework which could contain various modelling methods and statistic methods and could give the combined influence of deterministic and probabilistic nature, and then combine the two components and show the dual-nature character of fire. To make this task tractable, numerous compromises must be made. Further, we find that many required details of actual incidents are not collected and many important phenomena are not sufficiently understood, such that approximations and estimates must be employed to fill in the gaps.

2.DETERMINISTIC MODEL

In this case, we suppose there exist following assumptions:

1. The room is closed with only a small leakage opening at the floor level.
2. Pressure remains constant from the start of the fire till burn-out; Air and smoke are both considered as ideal gases.
3. There is no mass and energy exchangement through the interface between hot and cold gases; The mass and energy exchangement is through the buoyant jet.

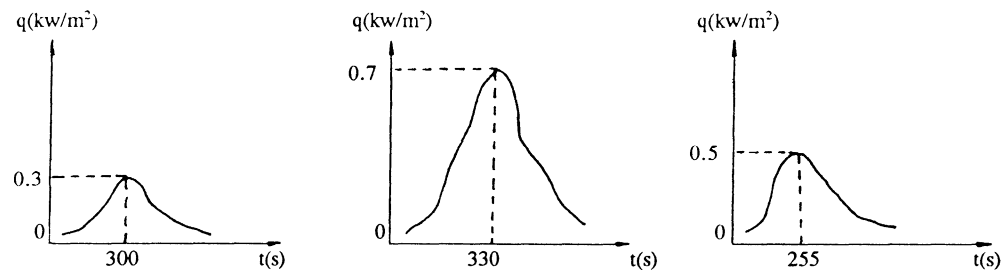
Since smoke is the most harmful factor in a fire, our deterministic model lays its emphasis on the study of rules of smoke layer. In a specified fire, the process of smoke spreading and its time-dependent temperature and depth are then determined. We could tell how smoke has developed at a certain time.

Different layouts of furniture cause different combustion scenario. The types of furniture layout can be divided into three kinds:

1. Locate at a comparatively distant place from all four walls.
2. Locate at a place near one of the four walls.
3. Locate in a corner near two of the four walls.

Under these three kinds of layouts, the same source will cause different combustion and mass quantity of cold air entrained by the buoyant jet, leading to different time-dependent temperature and depth of hot smoke layer which will be demonstrated in the equations presented later.

Consider a room with length and width of 4m, height of 3m, in which combustible furniture includes bed, table and sofa. Their surface materials are fibbers, wood and foam plastic and the area $2.5m^2$, $1.0m^2$ and $1.8m^2$ respectively. Their heat release rate which could be obtained by experiments, are shown respectively in Figure 1 (a),(b),(c).



(a) (b) (c)

Fig 1. Heat release rate of furniture

In the case of this paper, fire is in the initial stage when possibility of secondary ignition is very small. A differential equation could be given by experiments for estimating time dependent depth of smoke[1]

$$\frac{dy}{d\tau}+\frac{Q^*}{K}+K_1(\frac{Q^*}{K})^{\frac{1}{3}}\cdot(Y)^{\frac{5}{3}}=0 \tag{1}$$

$$\tau=t\cdot\sqrt{\frac{g}{H}}\cdot(\frac{H^2}{s})$$
$$Q^*=\frac{\dot{Q}}{c_p\cdot\rho_0\cdot T_0\sqrt{g\cdot H}\cdot H^2} \tag{2}$$

$\dot{Q}$ is heat release rate, H is height of the room, s is floor surface of the room, subscript 0 refers to environment parameters. K_1 is a constant with a value of 0.21. Y is the ratio of room height to smoke layer height. The value of K changes with the furniture layouts:

$$K=\begin{cases}1 & \text{furniture is far from all four walls}\\ 2 & \text{furniture is near one of the four walls}\\ 4 & \text{furniture is near two of the four walls}\end{cases}$$

Equation for smoke layer density can also be given:

$$\frac{\rho}{\rho_0}=1-\frac{K\cdot Q^*\cdot\tau}{1-Y} \tag{3}$$

We have supposed that room pressure does not change and both air and smoke are ideal gases, so we could get the expression for average smoke temperature:

$$\frac{T}{T_0}=\frac{1}{1-\frac{K\cdot Q^*\cdot\tau}{1-Y}} \tag{4}$$

where Q^*,τ can be found in equation (2).

3. PROBABILISTIC MODEL

We consider two of probabilistic factors: probabilistic nature of fire causes and probabilistic nature of furniture layouts.

(1).Probabilistic nature of fire causes.

Fire is caused by combustible furniture, but we can not predict which kind of furniture causes it. This is the probabilistic nature of fire causes. We could determine possibility of fire occurring according to ignition resistance of various furniture in one room.

We could simplify the circumstance by supposing there is little heat loss in the process of heat exchangement between combustible object and fire source, and the surface temperature of combustible object keeps rising toward the source temperature, and when it reaches the ignition temperature the combustible object will ignite. Thus, if we know the probability (which we call p_a) of the appearance of fire sources whose temperature is higher than the ignition temperature of the combustible object and the probability (which we call p_b)

of fire sources on the surface of the combustible object, then we could get the probability P_c of the combustible object to cause a fire from the following expression:

$$p_c = p_a \cdot p_b \tag{5}$$

Now, let's take an analysis of fire sources. Fire sources include two probabilistic factors: source distribution and energy. Source distribution usually depends on people's habits. We could reasonably consider that probability of sources at each point in a room are the same, thus p_b in expression (5) will be:

$$p_b = c \cdot s \tag{6}$$

where c is a constant, s is the surface area of the combustible object. (How to determine c will be mentioned in later part). Source energy is generally in direct proportion to source size and temperature. Suppose possibilities of sources of various sizes are the same, then we could reach the conclusion that probability of the appearance of various fire sources is the single function of their temperature.

In our daily life, there are various fire sources. They may be a low-temperature cigarette and various kinds of electric stars, and also may be a high power electric stove with temperature higher than 1000k. Possibilities for these fire sources with different temperature to appear at any point in the room are different. It could be reasonably inferred that possibilities for those with lower temperature are bigger. In an overall view, possibilities for these sources to appear at a certain point in the room may comply with a statistical function. According to Centre Limit Theorem[2], we could prove that possibility for fire sources with any temperature value to appear at a certain point in the room complies with Gauss-Function. The expression is:

$$p(T) = \frac{1}{\sqrt{2\pi}\,\sigma} e^{\frac{-(T-T_0)^2}{2\sigma^2}} \tag{7}$$

where σ is a constant. In Fig.2, horizontal coordinate represents temperature, vertical coordinate represents possibility. The peak of the curve corresponds to environment temperature T_0, which is the lowest value that source temperature could be, and indicates that possibility for the source with environment temperature to appear is the biggest. The left half of the curve is meaningless, for it's impossible for sources with temperature lower than T_0 to appear.

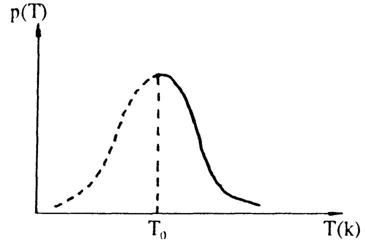


Fig 2. function of source temperature

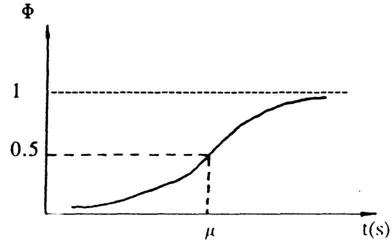


Fig 3. $\Phi((t-\mu)/\sigma)$ curve

From p(T) we could derive the expression for p_a in expression (5):

$$p_a(T)=\int_T^{\infty}p(t)dt=1-\int_{-\infty}^{T}p(t)dt=1-\Phi(\frac{T-T_0}{\sigma}) \tag{8}$$

$\Phi(t)$ is standard normal distribution.

Curve for $\Phi((t-\mu)/\sigma)$ is in Fig.3.

Values of $\Phi((t-\mu)/\sigma)$ can be checked out in Standard Normal Distribution Table[2]. Since these values can't be obtained directly by calculation, there exists great inconvenience in computer calculation. Therefore we hope to find an expression which could be calculated directly to substitute equation(8).

The shape of Fermi-function which is a statistical function applied often in quantum statistics[3] is very similar to that of $\Phi(t)$. Through calculation we could also find that they are not only similar in shape but also close in value.

Expression for Fermi-function is:

$$\lambda_f=\frac{1}{1+e^{\frac{t_0-t}{\tau}}} \tag{9}$$

t	Φ	λ_f
97	0.0013	0.0035
98	0.0228	0.0228
99	0.1587	0.1316
100	0.5	0.5
101	0.8413	0.8684
102	0.9772	0.9772
103	0.9987	0.9965

Table 1

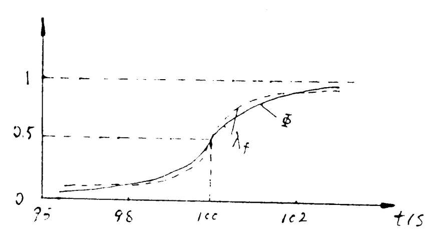


Fig 4. $\Phi((t-\mu)/\sigma)$ and λ_f curves

Any $\Phi((t-\mu)/\sigma)$ function can be substituted well by a Fermi-function. For example, when $\mu=100, \sigma=1$, $\Phi((t-\mu)/\sigma)$ can be substituted by a λ_f function in which $t_0=100$, $\tau=0.53$. Values of $\Phi((t-\mu)/\sigma)$ changing with t are listed in Table 1.

Draw the curves of $\Phi((t-\mu)/\sigma)$ and λ_f with values of Tab.1 in one figure (Fig 4), obviously these two curves are very close to each other. Thus, we could use λ_f to substitute Φ function in calculation.

Then expression (8) can be rewritten as following:

$$p_a=1-\frac{1}{1+e^{\frac{T_0-T}{\tau}}} \tag{10}$$

From expression (5),(6) and (9), probability for combustible object to cause a fire in a certain bedroom can thus be demonstrated by the following expression:

$$p_c = p_a p_b = cs\cdot(1-\frac{1}{1+e^{\frac{T_0-T}{\tau}}}) \tag{11}$$

Equation (11) shows that the combustible object with larger surface area will have bigger possibility to cause a fire, this is because there is relatively a better likelihood for fire sources to be on combustible object with larger surface. Fig 5 is the curve of p_c. When $T=\infty$, $p_c=0$, this means that places where no combustible objects locate in the room could be regarded as points where combustible objects with zero possibility to cause a fire locate. To a room with various combustible objects, summary of p_c value of all furniture is 1, that is:

$$\sum_i p_{c,i} = 1 \qquad (i=1,2,\cdots) \tag{12}$$

i corresponds to various furniture. From expression (11), expression (12) can be written as:

$$c\cdot\sum_i [s_i(1-\frac{1}{1+e^{\frac{T_0-T_i}{\tau}}})]=1 \tag{13}$$

where s_i is the surface area of furniture i, T_i is the ignition temperature of furniture i. We can determine τ in expression (11) and c in expression (13) according to statistical data.

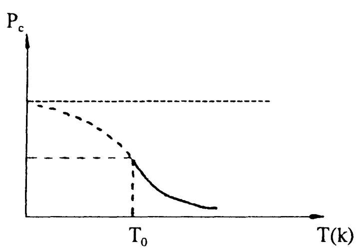


Fig 5. Probability of combustible object to cause a fire

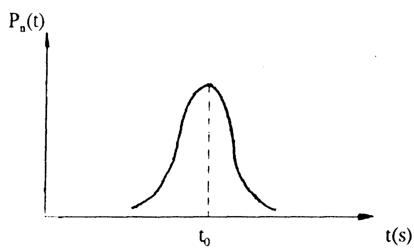


Fig.6 Probability of people who are injured

(2) Probabilistic nature of furniture layouts.

Probabilistic nature of furniture layouts depends on statistical data. In this case, we have the following simplification:

$P_{arr,1}=0.5$, when bed, table and sofa are all near one wall;
$P_{arr,2}=0.3$, when table is in a corner, while bed and sofa are near a wall;
$P_{arr,3}=0.2$, when sofa is in a corner, while bed and table are near a wall.

4. RISK ANALYSIS

Since there exist many differences between people, including physical state, age etc., the same fire may cause risk to different extent to different people. Some fires can not do any harm to ordinary people, but may do great harm to a weak patient; in some fires, strong people may hold on till they get to safety, but old or weak people may move too slowly and lose their lives in the fire.

No matter how serious the fire is, it may do harm to lives. Here again, statistical function can be applied to demonstrate the extent to which fires do harm to people at any time.

Suppose we can do such an experiment in which a group of various types of people are subjected to a same fire. At any time, some people may die. Record the number of people who are injured at each time point as n(t), and the ratio of n(t) to the total number of people N is the probability of people who are injured at that time, write this as $p_n(t)$. According to Centre Limit Theorem, we can also prove that $p_n(t)$ should accord with Gauss-function distribution. $p_n(t)$ curve is shown in Fig 6. The expression of $p_n(t)$ is:

$$p_n(t)=\frac{1}{\sqrt{2\pi}\,\sigma}e^{\frac{-(t-t_0)^2}{2\sigma^2}} \tag{14}$$

Expression of probability of hazard fire does to people is:

$$\lambda=\int_0^t p_n(t)dt=\int_{-\infty}^{t}=\Phi(\frac{t-t_0}{\sigma}) \tag{15}$$

We have proved that function Φ can be substituted by Fermi-function, so:

$$\lambda=\frac{1}{1+e^{\frac{t_0-t}{b}}} \tag{16}$$

where b is a constant.

In order to determine the expression for λ function, we suppose that the fire will do harm to 93% of people when smoke temperature reaches 473k or the height of its bottom reduces to 1.7m, that is $\lambda_1=93\%$; the fire will do harm to 97% of people when smoke temperature reaches 523k or its bottom height reduces to 1.5m, that is $\lambda_2=97\%$.

Calculate the time t_1 and t_2 when fire develops to the two dangerous states described above by deterministic model, the two equations for solving t_0 and τ can be listed:

$$\lambda_1=\frac{1}{1+e^{\frac{t_0-t_1}{b}}} \tag{17}$$

$$\lambda_2=\frac{1}{1+e^{\frac{t_0-t_2}{b}}} \tag{18}$$

From these two equations we get:

$$t_0=\frac{t_2\ \ln(\frac{1}{\lambda_1}-1)-t_1\ \ln(\frac{1}{\lambda_2}-1)}{\ln(\frac{1}{\lambda_1}-1)-\ln(\frac{1}{\lambda_2}-1)} \tag{19}$$

$$b=\frac{t_2-t_1}{\ln(\frac{1}{\lambda_1}-1)-\ln(\frac{1}{\lambda_2}-1)} \tag{20}$$

As soon as λ is determined, probability of hazard fire does to people can be calculated. Under one kind of furniture layouts j, risk probability is:

$$P_j=\sum_i p_{c,i}\lambda_{i,j} \tag{21}$$

For all kinds of furniture layouts, overall risk probability is determined by weighting the results for each furniture layout by the probability of that furniture layout:

$$P=\sum_j P_j P_{arr,j}=\sum_j \sum_i P_{c,i}\lambda_{i,j}P_{arr,j} \tag{22}$$

5. RESULTS AND DISCUSSION.

Time curves of risk probability under furniture layout j(j=1,2,3) is shown in Fig 7. Time curve of overall risk probability of probabilistic fire is in Fig 8. The three curves in Fig 7 indicate that degree of fire risk changes with furniture layout in a room. Layout 2 has relatively bigger risk probability while layout 1 has smaller risk probability. Therefore when materials are given, the most reasonable and least dangerous layout can be selected.

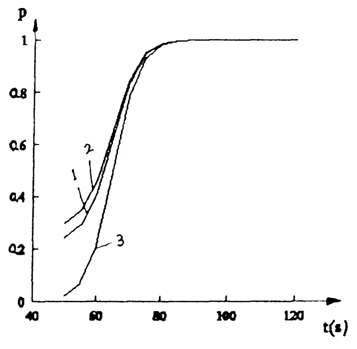


Fig 7. Curves of risk probability

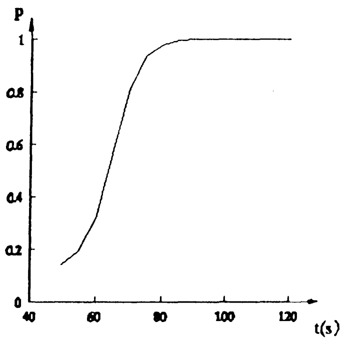


Fig 8. Overall risk probability

Fig 8 shows that before t=60s, a probabilistic fire has little risk. If people could evacuate in 60 seconds after the fire occurs, they will risk little danger; After t=60s, the fire risk rises quickly. If people could not leave in time, the circumstance is very dangerous to them. From this analysis, we could have a better knowledge of evacuation time.

6. CONCLUSIONS.

A deterministic and probabilistic model for room fires is developed and the initial application of this model for the estimation of fire risk associated with a specified room is described in this paper. Statistic functions are applied to calculate the probability of fire causes and analyze the dangerous state people expose to. The risk curves as a result of computation well reflect hazard degrees varying with furniture materials and layouts. This method provides a structure for developing detailed fire scenario descriptions which include not only room fires but also more complex fires. This effort is also beneficial in developing more practical models for economic use.

Emphasis is laid on probabilistic model with a simplified deterministic model used in this paper. Much more work is needed to be done to fill in the gaps in the probabilistic model. Shortcomings in the model arises from a lack of technical knowledge of fire phenomenology or a lack of detail in required data. But the identification of needs coupled with the potential value of the model should provide incentive for the advances in this area.

ACKNOWLEDGEMENTS

The financial support of this work by Natural Science Fund is very much appreciated.

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