QUANTITATIVE CALCULATION OF CHARACTERISTIC VOLUME OF SURFACE-FIRE BEHAVIOR

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ABSTRACT
In the description of the characteristic volume of fire behavior, fire intensity $I$, rate of spread $r$, and flame length $L$, etc. all have their scientific definitions, while the bound between the fireline and the residual region of a fire scene is not yet scientifically defined. This paper tries to find out theoretically the basis for dividing the bound, to give the fireline thickness $D$ a scientific definition, and to propose a method of quantitative calculation.

According to the generality of fuels, the time-dependent curves of fuels combustion rate are utilized to work out a formula by experience. On the basis of defining scientifically the fireline thickness, the Byram's formula is corrected, and a new one for calculating the fire intensity of surface fire, i.e. $I = 0.788HWR$, is presented. In this formula, $H$ is the combustion value of fuels, the calculating method of the thermal current intensity $J$ is given, and $J_{max} = 1.25 HWr/D$ the calculating formula of flame length is revised, and a new one $L = 0.775 \sqrt{T}$ is proposed. In the spreading process of the forest fire, when the time needed for getting over a fireline thickness is $T$, it is called residence time. It is given out in this paper the method for estimating and determining the rate of spread $r$ and the residence time $T$ in the combustor. And on this basis the characteristic volume ($W$, $I$, $R$, $D$, $T$, $L$ and $J_{max}$, etc.) of surface fire behavior can be evaluated.

KEY WORDS: Fireline thickness, Residence time, Thermal current intensity, Point source, Line source, Instantaneous rate of combustion, Average combustion rate.

1. Instantaneous Rate of Combustion, Average Combustion Rate and Residual Combustion Stage

The combustion process of fuels inside the combustor may be expressed by the following figures and lines. In Fig 1-1 curve 1 and 2 are used to show respectively the time-dependent process of instantaneous and average combustion rate, $B(t)$ and $\bar{B}(t)$, the instantaneous and average combustion rate of fuels in a unit area; $\sigma_0$, $\sigma_0$, $\sigma_1$, the surface density of fuels before kindling, during combustion process, and of surplus materials after combustion. If a fire is kindled at $t_0$, let $\omega_{0}$ and $\omega$ indicate separately the surface density of available fuels before the kindling of fuels and during the process of combustion. Thus obviously:

$$\sigma_0 = \sigma(t_0) \quad (1-1) \quad W = \omega(t_0) \quad (1-2) \quad \omega(t) = \sigma(t) - \sigma_0 \quad (1-3)$$

During the combustion process the quality of fuels reduces with the lapse of time, on condition that the area occupied by fuels inside the combustor remained unchanged:

$$B(t) = \lim_{\Delta t \to 0} \frac{\Delta m}{\Delta t \cdot \Delta s} = - \frac{d\sigma}{dt} = - \frac{d\omega}{dt} \quad (2-1)$$

During the period from $t_0 \to t$, the average rate of combustion of fuels in a unit area is shown by the following equation

$$\bar{B}(t) = \frac{1}{t-t_0} \int_{t_0}^{t} B(t)dt = \frac{1}{t-t_0} \left[ \omega(t_0) - \omega(t) \right] = \frac{1}{t-t_0} \left[ W - \omega(t) \right] \quad (2-2)$$

It is seen from curve 1 that if a fire is kindled at $t_0$, $B(t)$ reaches the maximum at $t$ (instant), to be put down as $B_{max} = B(t_i)$. During the period from $t_0$ to $t_1$, $B(t)$ increases as time goes on, the quantity of heat released by the available fuels on a unit area in a unit time is trending to be on the rise and it burns to the utmost at $t_i$ instant its, flame reaches the climax. From curve 2, we see that $\bar{B}(t)$ gets to the maximum at $t_i$ instant, noted as $\bar{B}_{max}$ $\bar{B}(t_i)$. Comparing curve 1 to curve 2, we find that during the period from $t_0 \to t_i$, though $B(t)$ decreases with the lapse of time, $\bar{B}(t)$ still increases. During the period of $t > t_i$, we make out from curve 1 that when the fire behavior decreases, the fuels extinguish gradually.
Owing to the time taken up in the extinct stage being longer, the change in quality of fuels rather small, and the area occupied by it gradually narrows in irregularity, it is therefore very hard to determine precisely the $\sigma(t)$ value, and thus unable to calculate accurately the $B(t)$ value. During the period from $t_0$ to $t_f$, various data may all be determined precisely and $\overline{B} = \overline{B}_w$ has a clear physical meaning. That is, referring to the time on the average, the quantity of heat released in a unit time is the maximum. For this reason, the combustion stage is defined as residual stage. But the residual stage is not to be discussed here in this paper. From equation (2-2) we may have

$$\overline{B} = \overline{B}_w = \frac{1}{t_f - t_0} \left[ \int_{t_0}^{t_f} B(t) dt \right]$$  \hspace{1cm} (2-3)

2. The Instantaneous Combustion Rate in the Region And the Fireline Thickness.

Before the surface-fire occurs, the surface density of available fuels is expressed as $W(\xi, \eta)$. In the spreading process of surface fire, the fireline usually moves forward with the wind. In Fig. (2-1), strip 1 shows the position in which the fireline lies at $t'$ instant. Take, at will, a small region $d\xi d\eta$ on the fireline. In process of investigating surface fuels, owing to the specimen area used for sampling is $1m \times 1m$ and $2m \times 2m$, but under general conditions, the fireline thickness is $<2m$.

Therefore, the surface densities of available fuels in region $d\xi$ before kindling (the fire) may be looked on as the same, and put down as $W = W(\xi_0, \eta_0)$ as the time used for the fireline to go across with the wind, a fireline width is far less than the fire-scene combustion time, the rate of spread for the fireline to get across the $d\xi$ region with the wind during the process, maybe looked on as the same and put down as $r = r(\xi_0, \eta_0)$; Choose a natural coordinate, let the head wind direction be the axis $x$ direction and the tangential be the axis $y$ direction. As the rate of spread of the fireline in the $x$ direction is far greater than that of it in the $y$ direction, the direction of the rate of spread of each point in region $d\xi$ may be looked on as the same and being along the axis $x$ direction.

Each point in region $d\xi$ is burning, burning point like this is called point source. Each point source on axis $y$ direction has the same regular pattern, forming a line source of $dg$ length shown by dotted line in Fig. (2-1). Thus, after the choice of a natural coordinate, the plane problem is simplified as a straight line one on which the line sources spread along the $x$ direction. At $x=x'$ the expressing formula for the line source kindled at $t=t'$ instant is;

$$B(x', t') \delta(x - x') \delta(t - t')$$ \hspace{1cm} (3-1)

The line source at $x=x'$, during the period of $t=t'$, the expressing equation for its instantaneous combustion rate at $t$ instant is;

$$B(x', t') = \int_{t(t')}^{t(t')} B(x', t') \delta(x - x') \delta(t - t') \, dx' \, dt'$$ \hspace{1cm} (3-1)

The line source at $x=x'$, the expressing formula for its average combustion rate in the period of $t'=t$, is;

$$\overline{B}(x', t) = \frac{1}{t-t'} \int_{t(t')}^{t(t')} B(x', t') \, dt'$$
If the fuels at \((\xi, \eta_0)\) are put into a combustor having similar burning conditions for burning, rewrite \(W(\xi, \eta_0)\) as \(W\), and let kindling instant \(t' = t_0\), then \(B(x', t')\), i.e. \(B(t')\), and from (2-2) we have

\[
\bar{B}(x', t) = \frac{1}{t - t_0} \int_{t_0}^{t} B(t') \, dt = \frac{1}{t - t_0} \left[ W - \omega(t) \right].
\]

If at \(t = t_2\) instant, \(B(x', t)\) reaches its maximum, put down as \(\bar{B}_{\text{max}}(t_2)\), and the surface density of available fuels at \(t_2\) instant in the combustor, noted down as \(\omega(t_2)\), then from the above formula we may have

\[
\bar{B}_{\text{max}}(t_2) = \bar{B}_{\text{max}} = \bar{B}(x', t_2) = \frac{1}{t_2 - t_0} \int_{t_0}^{t_2} B(t') \, dt = \frac{1}{t_2 - t_0} \left[ W - \omega(t_2) \right]. \tag{3-2}
\]

Then obviously, \(W, \omega(t_2)\) bear a relation not only to position \((\xi, \eta_0)\) of region \(\Delta s\), but to the nearly meteorological conditions at \(t_2\) instant.

At \(t = t'\) instant in region \(x \leq x'\), the expressing formule of the instantaneous combustion rate of the line source at \(x\) is

\[
B(x, t') = \int_{t_0}^{t'} \int_{\mathbb{S}'} B(x', t') \delta(t - t') \, dx' \, dt'. \tag{3-3}
\]

Fig. (2-2) shows the fire scene at \(t'\) instant in the direction of axis \(x\). As soon as the forward point \(A\) is kindled the instantaneous combustion rate \(B(x', t')\) has a trend to rise; Point \(B\) being Kindled prior to Point \(A\) burns to the utmost, its flame reaches the climax, i.e. \(B_{\text{max}} = B(z_1, t')\); Point \(C\) being kindled prior to point \(B\), its instantaneous combustion rate has had a trend to decline. Thus it can be seen that the instantaneous combustion rate of each line source in region \(\Delta s\) at an identical instant is different from one another.

The expressing equation of the instantaneous combustion rate of the region in the stage from \(x\) to \(x'\) at \(t = t'\) instant is

\[
\bar{B}(x, t') = \frac{1}{x' - x} \int_{x}^{x'} B(x, t') \, dx.
\]

It is seen from Fig. (2-3) that the line source with \(\Delta y\) for its length, the value of the instantaneous combustion rate in the burning region composed of continuous distribution in \(x\) direction has relation to the width taken in \(x\) direction. Calculating from the front edge, we found that the value of instantaneous combustion rate in the region too narrow in width is small, and that it is also small in the region unduly wide in width, while the value of it in the region from \(x_2\) to \(x'\) is maximum, noted down as follows:

\[
\bar{B}_{\text{max}}(x_2) = \bar{B}(x_2, t') = \frac{1}{x' - x_2} \int_{x_2}^{x'} B(x, t') \, dx. \tag{3-4}
\]

where \(\bar{B}_{\text{max}}(x_2)\) has a clear physical meaning. It expresses that the heat power of released in per unit area, which is referred to on the average, in the region from \(x_2\) to \(x'\), is maximum. Obviously, as to the scene of fire, this region is defined as fireline. \(\bar{B}_{\text{max}}(x_2)\) is defined as instantaneous combustion rate of the fireline. From Fig. (2-3) it may be seen that the region of \(x \leq x_2\) whose instantaneous combustion rates are all smaller than those of the fireline is therefore defined as the residual region. The width \(x' - x_2\) is called fireline thickness, put down as \(D\). The residence time is noted down as \(T\). then

\[
D = x' - x_2 = r(t' - t_0) \tag{3-5}
\]

\[
T = t' - t_0 = D/r \tag{3-6}
\]

where \(D, r\) and \(T\) whose values relate not only to position \((\xi, \eta_0)\) of region \(\Delta s\), but to the nearly meteorological conditions at \(t'\) instant.

3. Making Use of Combustor to Calculate \(\bar{B}_{\text{max}}(x_2)\), and to Revise Byram's Formula

When surface-fire spreads to region \(\Delta s\), the region \(\Delta s\) may be divided into several elements of surface \(\Delta s\), and we have

\[
\Delta s = \Delta y \cdot \Delta x, \quad \Delta s = \sum_{i=1}^{n} \Delta s_i,
\]

As \(W\) in region \(\Delta s\) is the same, \(D\) and \(T\) are in small quantity as compared with the scale corresponding to the scene of fire. Therefore, the physical and chemical properties of fuels in each element of surface are identical and their topographic and meteorological conditions are in similar manner, too. Thus it can be seen that the regular patterns of burning of fuels in each region of \(\Delta s\) are the same, only the instants to kindle the fire are in order of priority. They are kindled successively along the axis \(x\) direction. The element of surface at \(x'\) is kindled
\[
\tau = \frac{x' - x}{v} = t' - t
\]
\[
dz = rd(t' - \tau) = rd
\]

If they are put in several combustors and to be kindled simultaneously at \( t' \) instant, their time-dependent curves of instantaneous combustion rates are identical and all represented by curves \( B(t) \) [see Fig. (1-1)]. Imitating the process of spread, the combustor where \( \tilde{d}_t \) is kindled at \( t' \) instant, the combustor where \( \tilde{d}_t \) is at \( t' - t_1 \), \( \ldots \) and the combustor where \( \tilde{d}_t \) is at \( t' - t_{\omega-1} \), their time-dependent curves of instantaneous combustion rates are \( B(t), B(t - t_1), \ldots, B(t - t_{\omega-1}) \) respectively.

If we watch several combustors simultaneously at \( t' \) instant, the combustion rates of fuels in each combustor are found different from one another, put down separately as \( B(t'), B(t' - t_1), \ldots, B(t' - t_{\omega-1}) \).

When \( n \to \infty \), \( \Delta s \to 0 \), element of surface \( \tilde{d}_s \) may be regarded as line source. when the line-source at \( t' \) is kindled at \( t' \) instant, then the instantaneous combustion rates at \( t \) moment is \( B(x', t) \) [see formula (3-1)], and \( B(x', t) = B(t) \), when the linesource at \( x \) must be kindled at \( t' - t_1 \) instant then the instantaneous combustion rate at \( t \) instant is \( B(x, t) \) and \( B(x, t) = B(t - t_1) \). At \( t \) instant and in the region \( x \leq x' \), the instantaneous combustion rate of the line-source at \( x \) is noted down as \( B(x, t') \) [see formula (3-3)], and \( B(x, t') = B(t' - t) \). The instantaneous combustion rate of the fire line at \( t' \) instant may be given from formula (3-4).

\[
\bar{B}_{max}(x_t) = \frac{1}{x' - x_t} \int B(x, t') dx
\]

Substituting in \( B(x, t') = B(t' - t) \), formulae (4-1), (4-2) and (3-6) we have

\[
\bar{B}_{max}(x_t) = \frac{1}{x' - x_t} \int B(t' - t) d(t' - t) = \frac{1}{t' - t_1} \int B(k) dk = \frac{1}{t' - t_1} \int B(k) dk
\]

Let \( t' = t_0 \) and substituting in equation (3-2).

\[
\bar{B}_{max}(x_t) = \bar{B}_{max}(t_0) = \bar{B}_{max} = \frac{1}{t_0 - t_1} \int [W - \omega(t_0)]
\]

As time index fixed in the combustor is \( t_0 > t' \) and time index of spread is \( t' > t_1 \), so

\[
T = (t' - t_1) \text{ spread time index} = (t_0 - t') \text{ combustor time index}
\]

The above formula shows that when the fireline spreads to the place \( (\xi_0, \eta_0) \) the instantaneous combustion rate of the fireline here may be determined by utilizing the experimental method. Take fuels from \( (\xi_0, \eta_0) \), put them into the combustor and kindle them under the similar burning conditions; if the maximum average combustion rate of the unit-area fuels can precisely be determined, then it will just be equal to the instantaneous combustion rate at \( (\xi_0, \eta_0) \).

It may be seen from the definition\(^9\) of intensity of thermal current that its value is

\[
J = \lim_{\Delta t \to 0} \frac{\Delta Q}{\Delta t \cdot \Delta s} = H \frac{\delta \omega}{\delta t} = H \cdot B \quad J(x, t) = HB(x, t)
\]

On the element of surface \( \tilde{d}_s \) in the fireline, the heat power produced by fuels is put down as \( dN \), then

\[
dN = J(x, t) ds = H \cdot \delta y \cdot B(x, t) dx
\]

If at \( t' \) instant the front edge part of the fireline is at \( x_0' \), then at \( t' \) moment the instantaneous calorifive power produced in the fireline of section \( \delta y \) is taken down as \( N \)

\[
N = \int dN = \int J(x, t') ds = H \cdot \delta y \int B(x, t') dx
\]

Substituting in (3-4), (3-5), (3-6), (5-1) then the above equation becomes

\[
N = H \cdot \delta y \left[ \frac{x' - x_0'}{x' - x_0} \right] \int B(x, t') dx = H \cdot \delta y \cdot (x' - x_0) \bar{B}_{max}(x_0) = H \cdot \delta y \frac{D}{T} [W - \omega(t_0)]
\]

From the surface-fire definition of fire intensity, it may be known that \( I = N/\delta y \), then from the above equation we get

\[
I = H \frac{D}{T} [W - \omega(t_0)] \quad (6-1) \quad I = H [W - \omega(t_0)]
\]

Evidently, from Fig. (2-3) we make out that \( \omega(t_0) \neq 0 \), therefore on the basis of scientifically defining the fireline, Byram's formula must be revised.

4. Experimental Curves and Their Mathematical Expressing Formulae

After the fuels in the combustor are kindled, their total amount reduces with the lapse of time, and the available fuels burnt

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are increasing. Their surface density is noted down as $\Omega(t)$, then
$$\Omega(t) = \omega(t) - \omega(t) = W - \omega(t)$$
If we start taking down the time from the instant of kindling, i.e., let $t_0 = 0$, then the above form is rewritten as
$$\Omega(t) = \omega(0) - \omega(t) = W - \omega(t) \quad (7-1) \quad \Omega(0) = 0; \quad \Omega(\infty) = W \quad (7-2)$$
Substituting (7-1) in (2-1), (2-2), (6-1), and (6-2) we have
$$B(t) = \frac{dQ}{dt} \quad (7-3) \quad \bar{B}(t) = \frac{\Omega(t)}{t} \quad (7-4) \quad l = Hr\Omega(t) \quad \text{or} \quad l = HDG(t) / T \quad (7-5)$$
The longer the burning time of fuels, the greater the percentage occupied by the fuels burnt, and the percentage of the fuels burnt within a unit-time is recorded as
$$<D(t) / t> \quad (8-1)$$
Integrating the two sides against (8-1), we have the "including in one" condition,
$$\int_0^\infty f(t) dt = 1 \quad \text{When W-value is smaller than 5kg/m}^2, \quad \text{the experimental curve of fuels in the combustor is represented by the dotted line in Fig. (1-1)\textsuperscript{t}, while the theoretically formed curve by the real line. The theoretical curve may be expressed by the following equation;}
$$\frac{dQ}{dt} = \frac{4}{\sqrt{\pi}} W e^{-\frac{Q^2}{4}} \quad (8-2) \quad B(t) = \frac{dQ}{dt} = W - \frac{4}{\sqrt{\pi}} \lambda t^{\frac{1}{2}} e^{-\lambda t} \quad (8-3)$$
Taking against (8-3), the values whose first grade differential quotient is equal to zero, and the second smaller than zero.
$$\sqrt{\lambda} t^* = 1.00 \quad (8-4) \quad B_{max} = B(t^*) = 0.830 \sqrt{\lambda} W \quad (8-5) \quad J_{max} = 0.830 \sqrt{\lambda} HW \quad (8-6)$$
Integrating the two sides against (8-3) we have
$$\Omega(t) = W \left[ \frac{2}{\sqrt{\pi}} \int_0^{\sqrt{\lambda} t^*} e^{-x^2} dx - \frac{2}{\sqrt{\pi}} \sqrt{\lambda} t^* e^{-\lambda t^*)} \right]$$
$$2/\sqrt{\pi} \int_0^{\infty} e^{-x^2} dx \quad \text{is generally called error function, noted down as erf(x)} \quad (2/\sqrt{\pi}) \quad e^{-x^2} \quad \text{is called Gauss function, put down as G(x)} \quad \text{the above formula is rewritten as}
$$\Omega(t) = W [erf(\sqrt{\lambda} t^*) - \sqrt{\lambda} t^* G(\sqrt{\lambda} t^*)] \quad (9-1)$$
Through consulting the table we may get it\textsuperscript{b}
$$\Omega(t^*) = 0.428 W \quad (9-2)$$
Let (9-1) be substituted in (7-4) we have
$$\bar{B}(t) = \frac{W}{t} [erf(\sqrt{\lambda} t^*) - \sqrt{\lambda} t^* G(\sqrt{\lambda} t^*)] \quad (9-3)$$
Taking against (9-3) the values whose 1st grade differential quotient is equal to zero and the 2nd smaller than zero, and noted down as $t_1, t_2$ [see Fig. (1-1)]
$$\sqrt{\lambda} t_1 = 1.50 \quad (9-4) \quad B_{max} = B(t_2) = 0.525 \sqrt{\lambda} W \quad (9-5) \quad \Omega(t_2) = 0.788W \quad (9-6)$$
Let (9-4) be substituted in (5-2). From (9-4), (9-7) we again obtain
$$T = t_2 - t_0 = t_2 \quad (9-7) \quad \sqrt{\lambda} = 1.50 / T \quad (9-8)$$
Equations (9-6), (9-7) and (9-8) give the method of determining $T$ and important parameter $\sqrt{\lambda}$. First of all, the effectuation degree factor $\alpha$ of fuels is determined, now $W= a_0$, the surface density of available fuels burnt is computed as $\Omega(t_2) = 0.788 a_0$, thus the surface density of residual fuels at $t_2$ instant is recorded as $\Sigma$
$$\Sigma(t_2) = a_0 (1 - 0.788a) \quad (9-9)$$
Then putting the fuel on one square meter at $(\xi_0, \eta_0)$ into an area of one square meter in the combustor, initiating the burning conditions at $(\xi_0, \eta_0)$: Start taking down the time at the instant of kindling, when the residual quality is indicated by the display as value $\Sigma$, we note down the instant $t_2$ and thus determine the value $T$. Then the value $\sqrt{\lambda}$ is calculated. There are at present various methods for calculating the spread rate of the surface fire. Making use of the combustor to estimate the spread rate of fuels is a more accurate method.\textsuperscript{b}
$$r = r(k_1 k_2 / k_0) \quad (9-10)$$
r is the rate of spread at windless moment, $k_1$ is the altered factor of windspeed, $k_2$ of compactness, and $\varphi$ is the topographic angle of slope. $T$, $\sqrt{\lambda}$ and $\tau$ be substituted in the formulae of (3-5), (7-5) and (8-6), we respectively have
$$D = \tau T \quad I = 0.788 WHR = 0.788 WHD / T \quad J_{max} = 1.25 WHR / D = 1.60I / D$$
According to Byram's definition, the relation between the fire intensity and the length of flame is

\[ L = 0.0755 r^{0.46} \]

Where as defined in this paper the relation between them is

\[ L = 0.0755 \sqrt{r} \]

To sum up (the above mentioned), collecting beforehand the fuel specimen all around the surface and marking their locations \((\xi, \eta)\). Each specimen is put into the combustor to be tested under various burning conditions then the data groupings under different burning conditions at \((\xi, \eta)\) are obtained; i.e. \(\{E| (\xi, \eta)\}, \{T| (\xi, \eta)\}, \sqrt{\lambda| (\xi, \eta)}\), and from them other data groupings of characteristic volume of fire behavior at \((\xi, \eta)\) are calculated; i.e. \(\{I| (\xi, \eta)\}, \{J_{\text{max}}| (\xi, \eta)\}, \{D| (\xi, \eta)\}, \{L| (\xi, \eta)\}\). Under the changeable meteorological conditions, an estimation is to be made for the sitation of the scene of fire. And among different burning conditions, the pre-ignition conditions of fuels must well be considered.

5. Visual Fireline Thickness \(D\) on The Scene of Fire

The bounds between the fireline and residual fire region as defined in this paper is very hard to be visual, but the front edge part \(z\)' of the fireline and the producing position \(z_1\) of the highest flame are easy to be visual, and the distance between them is noted down as \(l\), and from formula \((8-4)\), \((9-4)\) we have comparing Fig. (1-1) with Fig. (2-3) we have

\[ l = z' - z_1 \quad (10-1) \]

\[ t_2/t_1 = 1.50 \quad (10-2) \]

\[ \frac{z' - z_1}{z - z_1} = \frac{t_2 - t_1}{t_1 - t_0} \quad (10-3) \]

Let \(t_0 = 0\), and substituting in formula \((3-5)\), \((10-1)\), and \((10-2)\), we get

\[ D = 1.5l \quad (11) \]

The fireline thickness is (equal to) 1.5 times as the distance from the fire head to the peak of flame.

If \(L\) and \(r\) are further visual, then \(l\), \(J_{\text{max}}\), and \(T\) can right be estimated from formula \((10-1)\) to \((10-5)\).

As the limits between residual region and extinguishing regions inside the scene of fire is very hard to decide, the features of the method introduced here in this paper are found expression as follows.

A. To estimate the fireline thickness \(D\);

B. To calculate the important parameters of the fire behavior — \(J_{\text{max}} \approx I/D\), the thermal current intensity at the peak of flame in the fireline;

C. No matter what it is, to calculate or to estimate on the scene of fire, the main characteristic volume of fire behavior can exactly be calculated.

REFERENCE