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Procedia Engineering 45 (2012) 663 – 668

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**Procedia  
Engineering**


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## 2012 International Symposium on Safety Science and Technology Investigation on compressed air foams fire-extinguishing model for oil pan fire

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*Shanghai Fire Research Institute of MPS, Shanghai 200438, China***Abstract**

In this article, based on simplifying of extinction agent's extinguishing mechanism and the fuel's combustion characteristic, an extinguishing model is established. Three kinds of fuels - 93 # gasoline, 0 # diesel oil, 95% ethanol, are applied. The compressed air Aqueous film forming foams (AFFF) is used as the extinction agent, The heat release rate of the fuels is obtained by the free burning test, the extinguishing time under different effective extinguishing intensity is obtained by the implementing actual extinguishing test. Investigation is implemented on extinguishing models of compressed air AFFF for diesel oil/gasoline extinguishing and insoluble AFFF for ethanol extinguishing, therefore the calculation method for the fire extinguishing models of different extinction agent for different fuels is obtained.

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*Keywords:* AFFF; compressed air foam; extinguishing model; oil pan fire

**Nomenclature**

$\dot{Q}_0$	the total heat release rate before extinguishing( kW)
$t_0$	the start moment of extinguishing(s)
k	constant related to the fuel( $s^{-1}$ )
a	constants related to fuel and extinction agent type
b	constants related to fuel and extinction agent type
$\dot{m}_w''$	the effective flux which is directly acted on fuel surface by foam extinction agent, i.e. extinguishing effective intensity( $kg/(m^2 \cdot s)$ )
<i>Subscripts</i>	
0	the start of extinguishing

**1. Introduction**

Because of the long duration, destructiveness and other characteristics of the oil pool fire, countries in the world invested a lot of human and material resources and carried out an extensive research on it in depth. During the design process for the fire-extinguishing and fire safety of the oil pool fire, it is desirable not only to know the combustion characteristic of the large oil pool fire, but also to evaluate the fire-extinguishing difficulty by quantization, in order to provide guidance for fire safety system design and fire party's fire-extinguishing tactics. But the extinction agent, as the key to success of firefighting,

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has quite a lot of types and composition. Even the same type of extinction agent manufactured by different manufacturer, the fire-extinguishing effects are different. So how to evaluate the fire-extinguishing effects is the focus of the industry as well. Further, because of the complexity of extinction agent’s extinguishing mechanism and the difference between different fire fuels’ combustion characters and mechanism, it is always a difficult thing to establish a proper and high reliable extinguishing calculation method and calculation model for fire research.

In this article, we select 3 widely used liquid fuels among oil fuels - 93 # gasoline, 0 # diesel oil, 95% ethanol, and use the compressed air AFFF as the extinction agent to investigate on extinguishing models of compressed air AFFF for diesel oil, gasoline and ethanol fire in order to obtain the calculation method for the fire extinguishing models of different extinction agent for different fuels.

**2. Calculation model**

Foam extinction agent is a very important fire-extinguishing medium. Its extinguishing theory is complicated. It contains both physical reaction and chemical reaction with both cooling effect and oxygen isolation effect because the oil pan is covered with combustion product and the combustion reaction chain is destroyed[1-4]. It is very difficult to use classic calculation model to calculate. For diesel fire and gasoline fire, it is the liquid fuels’ steam supporting the combustion. The composition is complex. It can not be indicated as one single molecular formula. Thus it is considered to simplify this complex extinguishing process and research on relationship between extinction agent and heat release rate. Refer to the fire-extinguishing process for sprinkling shelf fire investigated by H.Z Yu[5], etc. on 1994 and establish the extinguishing model. It considers effect to the heat release rate caused by the flux of the extinction agent and the sprinkling time. The formula is as following:

$$\dot{Q} = \dot{Q}_0 e^{-k(t-t_0)} \tag{1}$$

where  $\dot{Q}_0$  is the total heat release rate before extinguishing, the unit is kW.  $t_0$  is the start moment of extinguishing, t is time, k is constant related to the fuel, its unit is  $s^{-1}$ . The variation relation between the heat release rate and time is established. k is expressed as follows:

$$k = a \dot{m}_w'' - b \tag{2}$$

where a and b are constants related to fuel and extinction agent type, they should be determined by experiments. Normally, this extinguishing algorithm is applied when fuel or extinction agent is complicated, it simplifies the extinguishing model and it is established based on effective extinction agent flux and heat release rate. We use this algorithm when we research on foam for putting out oil pan fire as well, but considering that during the fire-extinguishing process, actually, extinguishing time and flux are important parameters which are cared much about, thus the relationship between extinguishing effective flux per unit area  $\dot{m}_w''$  and extinguishing time is established as:

$$t = \frac{\ln \frac{\dot{Q}}{\dot{Q}_0}}{-k} = \frac{\ln \frac{\dot{Q}}{\dot{Q}_0}}{b - a \dot{m}_w''} \tag{3}$$

In relation to foam for extinguishing oil fire,  $\dot{m}_w''$  is the effective flux which is directly acted on fuel surface by foam extinction agent, i.e. extinguishing effective intensity, the unit is  $kg/(m^2 \cdot s)$ . Based on the above mentioned calculation model, in order to obtain the calculation formula for foam extinguishing oil pan fire, fuel heat release rate should be obtained, then the fire extinguishing time under different extinguishing effective intensity  $\dot{m}_w''$  can be achieved from actual fire extinguishing experiments, Thus, three kinds of fuels free combustion experiments were implemented, meanwhile, fire extinguishing experiments under different flux accompanied by 6% compressed air AFFF was carried out as well. Because ethanol can melts in water, insoluble AFFF was applied.

**3. Experiment content**

*3.1. Free combustion experiment*

30 minutes free combustion experiments were carried out respectively for gasoline, diesel and ethanol with diameter 0.7 meter and 1.0 meter, refer Fig. 1. Curve showing their mass variation with combustion time was drew, using least squares method to implement linear regression analysis on mass loss trend,  $R^2$  is always tend towards 1 which means the reliability

of the established formula “ $m = -kt + c$ ” is very high. Mass loss curve is beeline, which means during the combustion process, the mass loss is constant with the same fuel and the same pan, i.e.  $\frac{dm}{dt} = -k$ . Based on the measured mass loss rate, working out their combustion rate and combustion linear rate, combustion rate multiplied with effective combustion heat, heat release rate can be obtain (see Table 1).



Fig. 1. Free combustion experiments.

Table 1. Diesel, Gasoline and Ethanol’s combustion character

	93# Gasoline		0#Diesel		Ethanol (95%)	
	Diameter 0.7m	Diameter 1.0m	Diameter 0.7m	Diameter 1.0m	Diameter 0.7m	Diameter 1.0m
Mass Loss Rate (kg/s)	0.0153	0.034	0.01012	0.0226	0.0097	0.0206
Combustion Rate(kg/(m <sup>2</sup> ·s))	0.0397	0.0433	0.0263	0.0288	0.0252	0.0262
Combustion liner rate(mm/min)	3.179	3.465	1.855	2.032	1.844	1.920
Heat Release Rate (kW)	700		500		288	
Density		0.75		0.85		0.82

### 3.2. Fire extinguishing experiment

Implement fire extinguishing experiments for 3 kinds of fuels with 0.7m diameter oil pan under different sprinkling flux. Extinguish diesel and gasoline fire by 6% compressed air AFFF. Extinguish ethanol fire by 6% insoluble AFFF. Expansion rate of foam is from 5 to 8, the spraying method adopts straight stream spraying. Sprinkling from the nozzle follow the outer tangent direction of oil pan edge. Nozzle flux is adjustable. Sprinkling effective flux is measured by weighting method. And the extinguishing time is recorded. The sprinkling scene by compressed air AFFF is shown in Fig.2. Experiment of extinguishing oil pan fire is shown in Fig. 3.



Fig. 2. Compressed air sprinkling scene.



Fig.3. Extinguishing experiment scene.

### 4. Result of experiments

The experiment result of 3 kinds of fuels, i.e. curve for extinguishing time varies with extinguishing effective intensity is fitted. Based on NLSF(Nonlinear Least Squares Fitting) method, we take formula (1) as fitting function and set initial parameters Q, a, b. Then we carry out multiple iterations fitting based on Levenberg-Marquardt (L-M) arithmetic, i.e., we calculate partial derivative of 3 parameters-to-be-estimated till residual sum of squares ( $\chi^2$ ) is minimum, in order to get optimal fitting value. Red solid lines are used to indicate the curve fitted based on formula (1)'s function relationship. Blue solid lines are used to indicate the upper and lower confidence interval with confidence level 0.9. Green lines are used to indicate the prediction interval with prediction level 0.9. Further, the remaining error chart for each measure point is indicated at the lower part of the figure.

#### 4.1. Diesel fire

According to the diesel fire's combustion rate measured from free combustion, which is illustrated in Table 1, for diesel fire with diameter 700, heat release rate  $Q_0$  is 500 kW. Figure.4 shows the fitting result. Based on fitting multiple iterations, the fitting result is best when Q is set 5. Determine factor  $R^2$  to be 0.94, indicate that formula (1) is fit close to the result of the experiment. Further, obtain that the best fitting value for a and b is 2.35 and 0 respectively; the broad of confidence interval with confidence level 0.9 is  $\pm 5s$ ; the error between experiment measuring points and the fitting curve is around -10s to 10s. Obtain the relationship between AFFF extinguishing time t for diesel oil fire and  $\dot{m}''_w$  as following.

$$t = \frac{\ln \frac{\dot{Q}}{\dot{Q}_0}}{-2.35\dot{m}''_w} \tag{4}$$

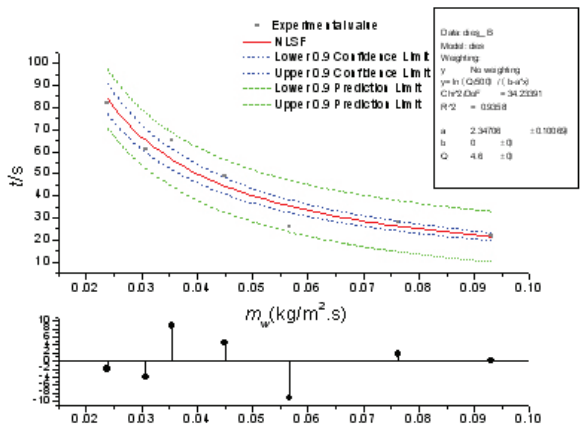


Fig. 4. Diesel oil fire extinguishing experiment, variation curve between effective fire extinguishing intensity and fire extinguishing time.

#### 4.2. Gasoline fire

Based on the gasoline fire combustion rate measured from free combustion (see Table 1), for gasoline fire with diameter 0.7 meter, heat release rate Q is 700kW. The fitting result can be seen in Fig.5. Determine factor  $R^2$  is 0.99. Formula (1) is quite fit close to the extinguishing experiment result. Further, obtain that the best fitting value for a and b is 1.537 and 0.00805 respectively; the broad of confidence interval with confidence level 0.9 is  $\pm 8s$ ; the error between experiment measuring points and the fitting curve is around -6s to 8s. Obtain the relationship between AFFF extinguishing time t for gasoline oil fire and  $\dot{m}''_w$  as following.

$$t = \frac{\ln \frac{\dot{Q}}{\dot{Q}_0}}{0.00805 - 1.537\dot{m}''_w} \tag{5}$$

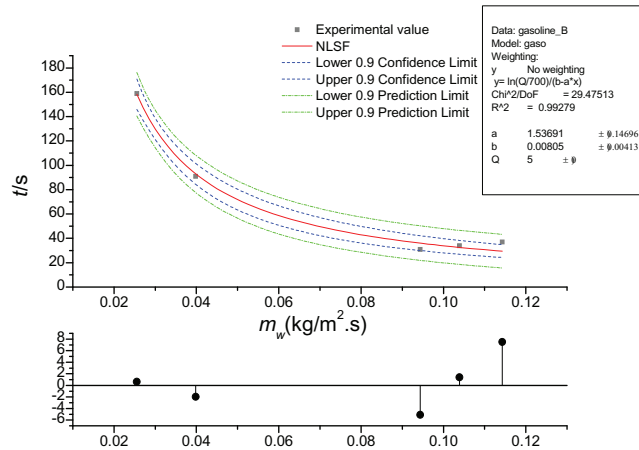


Fig. 5. Gasoline fire extinguishing experiment, variation curve between effective fire extinguishing intensity and fire extinguishing time.

### 4.3. Ethanol fire

Based on the ethanol fire combustion rate measured from free combustion (see Table 1), for ethanol fire with diameter 0.7 meter, heat release rate Q is 288kW. Regularity is apparent. But the accuracy is not as good as gasoline and diesel oil model. The broad of confidence interval is wide; the error between experiment measuring points and the fitting curve is big. The best fitting value for a and b is 0.585 and 0.00452 respectively. Obtain the relationship between AFFF extinguishing time t for ethanol fire and  $\dot{m}_w''$  as following.

$$t = \frac{\ln \frac{\dot{Q}}{\dot{Q}_0}}{0.00452 - 0.585 \dot{m}_w''} \quad (6)$$

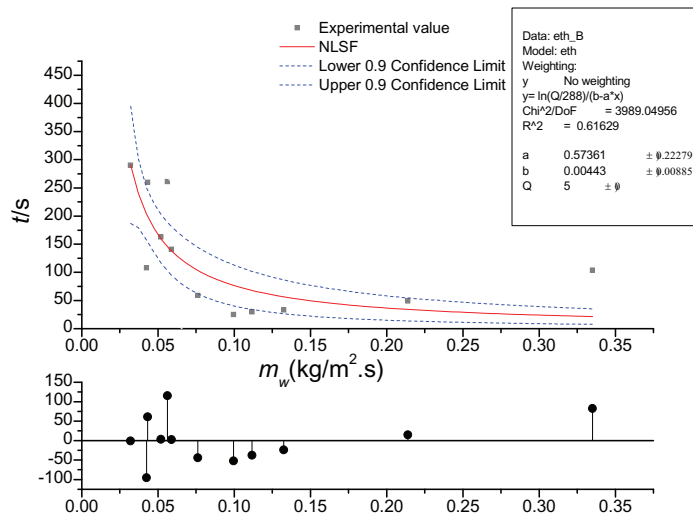


Fig. 6. Ethanol fire extinguishing experiment, variation curve between effective fire extinguishing intensity and fire extinguishing time.

The result of the experiment indicates that the fire extinguishing model of water applied to complex fuels is applicable to AFFF as well. This calculation method and calculation model is applicable not only to complex fuels but also to extinction agent with complex extinguishing mechanism. The value of  $k$  is related to fuel type and the extinction agent.  $k$  value can be used to judge fuel's extinguishing difficulty and the extinction agent's extinguishing efficiency. If  $k$  value is big, extinguishing difficulty is low, extinction agent's extinguishing efficiency is good; if  $k$  value is little, extinguishing difficulty is high, extinction agent's extinguishing efficiency is bad. When AFFF is used for fire extinguishing, for the difficulty of fire extinguishing, ethanol is the highest, and then is gasoline, diesel oil is the lowest. Further, among the express of  $k$ , constant  $a$  take the key effect,  $b$  is a correction value to  $a$ . The  $k$  is positive can be a critical condition to judge whether the fire extinguishing effective intensity is sufficient for extinguishing a fire.

## 5. Conclusions

The process for complex extinction agent extinguishing complex fuels was simplified, and we only focus on fire extinguishing result, the relationship among extinguishing time, extinguishing effective flux and heat release rate, and then the calculation model was established. Based on the free combustion experiment for gasoline fire, diesel oil fire and ethanol fire with diameter 700mm and the fire extinguishing experiment under different effective flux, the nonlinear fitting on fire extinguishing calculation model to experiment result was carried out, and the calculating formula of fire extinguishing time and flux for AFFF extinguishing of diesel oil fire and gasoline fire can be obtained, also the calculating formula of fire extinguishing time and flux for insoluble AFFF extinguishing of ethanol fire can be achieved, with validated applicability and accuracy. The key parameter  $k$  is related to effective flux on extinction agent per unit area. Parameters  $a$  and  $b$  was confirmed by experiments, as well as the values concern the type of fuels and extinguishing agent.

Based on the investigation, it is proved that the simplified extinction agent extinguishing model is practicable, it can be applied for complex extinction agent and complex fuels' extinguishing calculation. It can be applied to research on the fire extinguishing effect of extinction agent and to compare different fuel's fire extinguishing difficulty. The next step will be applying the fire extinguishing model to large fire's extinguishing experiment to compare and validate the calculation model's applicability and accuracy.

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