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An Energy Model in Fire Detection and Integrated Analysis on False Alarms

Abstract

Fires in a closed space are theoretically considered as a thermodynamic system in this paper. Genuine fires and fire like factors cause entropy increment, which demonstrates the release of kinds of energy including heat, light radiation and material loss. Genuine fires release much more energy than deceptive fire like factors.

An energy model was constructed and applied to smoke detection. Theoretical analysis and test result showed that this model and the algorithm of energy release prediction were suitable to fire detection study, and multi-sensor technique and adaptive alarm threshold method are effective way to reduce the rate of false alarm and the rate of failure to alert.

1. Introduction

The causes of false alarm are very complicated in automatic fire detection. Major aspects are:

a) Non-fire aerosols like cooking fumes, steam, dust, insecticide and cigarette smoking,
b) Environmental factors including electromagnetic interferences, airflow and rapid change of environmental temperature caused by air-conditioning,
c) Aging of components,
d) Poor quality in product design and production, and
e) Poor engineering design including wrong selection of the model and location of detectors, and poor quality in installation, commissioning and maintenance.

This paper only focuses attention to the false alarm problems that are related to signal of sensors and signal processing. In order to quantitatively analyze the false alarm, an energy model in fire detection was constructed. Theoretical relations of the rate of false alarm and the rate of failure to alert were deduced from this model. Application of this model in smoke detection showed evidence that this energy model was an effective method to reduce false alarm related to signal of sensors and signal processing [1].

2. The energy model

Fires in a closed space are theoretically considered as a thermodynamic system in this paper. Genuine fire and deceptive fire like phenomena in this system cause the increments of entropy, which demonstrates the release of kinds of energy such as heat, light radiation and material losses (smoke and gasses etc.). The increments of entropy are different for genuine fires and for deceptive fire like phenomena. When a genuine fire happens, the system releases energy for a fairly long time, and total energy released reaches a higher scale. When a deceptive phenomenon happens, the system releases energy only for a short time, and not so much energy are released[2].

In the real world, theoretically closed space does not exist. All systems are affected by environmental factors. We may possibly find the system's entropy increase or decrease. This means that there are energy flows outside the system caused by environmental factors and it should be considered in fire detection. In fact, some fire detectors have a variable steady value tracing environmental changes. In most cases genuine fires and deceptive fire like phenomena do not last very long, the system's steady values do not change too much. Therefore the system can be considered as a closed thermodynamic system during observation period. The energy release will depend on the system itself rather than outside world (see figure 1).

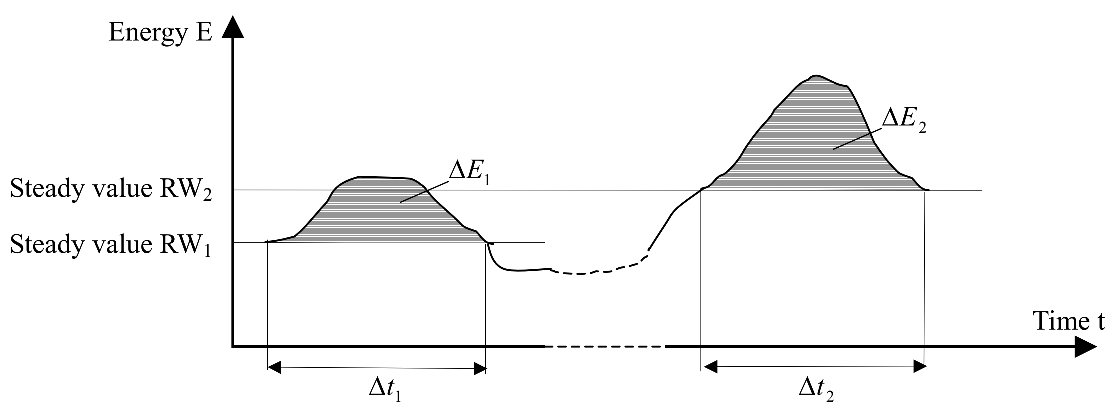

Fig. 1 Energy release of a closed system

The energy releases ΔE for a closed thermodynamic system are kind of random variable having statistical feature.

Suppose the functions of probability density of the energy release ΔE under non-fire and fire are respectively $P(\Delta E, x=0)$ and $P(\Delta E, x=1)$, where x are Boolean values that stand for non-fire and fire. For a given alarm threshold ΔE_T (see figure 2), the rate of false alarm is

$$P_{fa} = \int_{\Delta E_T}^{+\infty} P(\Delta E, x=0) d\Delta E \,, \tag{1}$$

while the detectivity rate of fire alarm is

$$P_d = \int_{\Delta E_T}^{+\infty} P(\Delta E, x=1) d\Delta E \,. \tag{2}$$

The rate of failure to alert is $P_E = 1 - P_d$. Since $\int_{-\infty}^{+\infty} P(\Delta E, x=1) d\Delta E = 1$, we get

$$P_E = \int_{-\infty}^{\Delta E_T} P(\Delta E, x=1) d\Delta E \,. \tag{3}$$

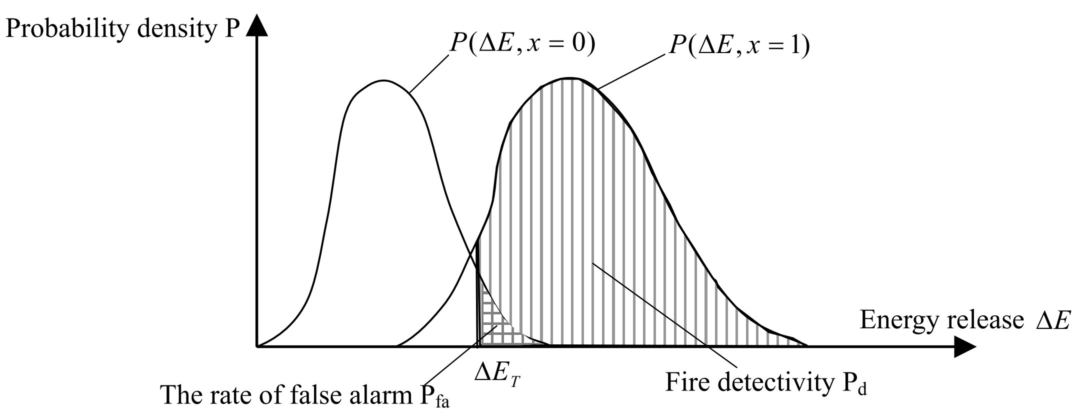

Fig. 2 Probability distribution of the energy released in a closed thermodynamic system

For a system with adaptive threshold values, the function of probability density of a threshold $\Delta \hat{E}_T$ is $P(\Delta \hat{E}_T)$. Then the instantaneous rate of false alarm is $\hat{P}_{fa} = \int_{\Delta \hat{E}_T}^{+\infty} P(\Delta E, x=0) d\Delta E$, and the general rate of false alarm is

$$P_{fa} = E[\hat{P}_{fa}] = \int_{-\infty}^{+\infty} P(\Delta \hat{E}_T) \int_{\Delta \hat{E}_T}^{+\infty} P(\Delta E, x=0) d\Delta E d\Delta \hat{E}_T \,. \tag{4}$$

In the same way, the general detectivity is

$$P_d = E[\hat{P}_d] = \int_{-\infty}^{+\infty} P(\Delta \hat{E}_T) \int_{\Delta \hat{E}_T}^{+\infty} P(\Delta E, x=1) d\Delta E d\Delta \hat{E}_T \,, \tag{5}$$

and the general rate of failure to alert is

$$P_E = 1 - P_d = \int_{-\infty}^{+\infty} P(\Delta \hat{E}_T) \int_{-\infty}^{\Delta \hat{E}_T} P(\Delta E, x=1) d\Delta E d\Delta \hat{E}_T \,. \tag{6}$$

It is clear, from above equations, that by using an adaptive alarm threshold $\Delta \hat{E}_T$ the rate of false alarm can be considerably reduced while the detectivity keeps at a given value, or the detectivity can be considerably improved while the rate of false alarm keeps at a given value.

With the method of constant rate of false alarm used in the signal processing in radar, we can reduce the rate of false alarm to a given value provided that the function of probability density and statistical feature of energy release ΔE are available.

According to the equations of thermodynamics, temperature rise is proportional to energy release. Smoke and gas release are mass losses in a closed thermodynamic system. From the mass-energy relation $E = mC^2$, mass loss is proportional to energy release too. The total energy release of a system is the sum of heat energy release, mass loss (such as smoke, gas and so on) and other energy release (such as light etc.). Existent fire detectors, such as heat detectors, smoke detectors, gas detectors and light detectors, all take indirect measurement of energy release.

For different type of fire, the percentages of each part of energy release are different. That is the reason why the fire detectors with single sensor cannot respond to all type fires. The success of multi-sensor detectors shows that the more accurate energy releases we measure, the lower rate of false alarm and higher detectivity we gain. Multi-sensor and adaptive alarm threshold (multi-criteria) become major development trend of fire detection [3][4].

3. Application of thermodynamic model in smoke detection

Smoke is one of the major characters at incipient stage for most fires. Other energy releases, such as temperature change, light radiation etc., are too weak to be measured in the incipient stage. So the smoke amount can be regarded as the energy release ΔE.

Suppose that the smoke amount is S, the test starts at the moment of T_0 and ends at T_1, and the output analogue value of smoke detector is V(t). We then have $S = \int_{T_0}^{T_1} V(t)dt$.

Optical smoke detectors with analogue value ranging from 0 to 255 were used in our test program. Statistical analysis was carried out on the basis of response curves against test fires of EN54-9 and some deceptive fire like sources. The result is given in table 1.

Table 1 Smoke amounts against test fires and non-fire sources

Fire source	Smoke amount □Digit*second□	Fire source	Smoke amount □Digit*second□	Non-fire source	Smoke amount □Digit*second□
TF1	4095	TF4 (3)	2373	Steam	3910
TF2	37440	TF5	4992	Mosquito incense	3960
TF3	100880	TF6	0	Mosquito incense (ventilated)	2100
TF4 (1)	2688	TF7 (1)	18020		
TF4 (2)	2835	TF7 (2)	16492	Cigarette smoking	18170

From table 1, we know that the energy release ΔE of non-fire sources except cigarette smoking is of the magnitude about 10^3. And ΔE for fire sources with the main product of smoke (TF2, TF3, TF7) are of the magnitude between 10^4 to 10^5. However, for other sources, the smoke amount cannot be regarded as total energy ΔE because, for example, the temperature change for fire sources of TF1, TF4, TF5 and TF6 is an important part of the energy release and can not be ignored. As a special case there is only temperature change but no smoke product in the experiment of TF6. Smoke detector cannot respond to TF6 no matter what fire detection algorithm is adopted. The reason is just that the energy release ΔE cannot be predicted by smoke sensing. For the non-fire source of cigarette smoking, the energy release ΔE reaches the magnitude that many fire sources reach as this experiment was carried out under a strict condition (smoking just in front of smoke detector). This implies that over smoking may lead to false alarm.

Fire alarm must be initiated in a real time. It is not permitted to obtain the total amount of smoke (total energy release) for making a fire alarm. Instead, the method of prediction of energy release is utilized in fire detection algorithms. Obviously, the amplitude and changing trend of smoke signal are the main factor of prediction. On the other hand, the longer the observation period lasts, the more accurate the prediction is. Therefore using adaptive alarm threshold and suitable observation period can effectively reduce the false alarm [2].

A new algorithm of smoke detection based on the energy release prediction is shown in Fig. 3. The key point of the algorithm is that the detector makes the prediction of energy release i.e. smoke amount from time to time. The result of the prediction is $\Delta\widetilde{E}$. For a given risk of alarm f_{risk}, the alarm threshold ΔE_T can be obtained. With the equations of (4) to (6), the rate of false alarm, the detectivity and the rate of failure to alert can be calculated. Fire alarm decision can finally be made by the information of P_{fa}, ΔE_T and f_{risk}.

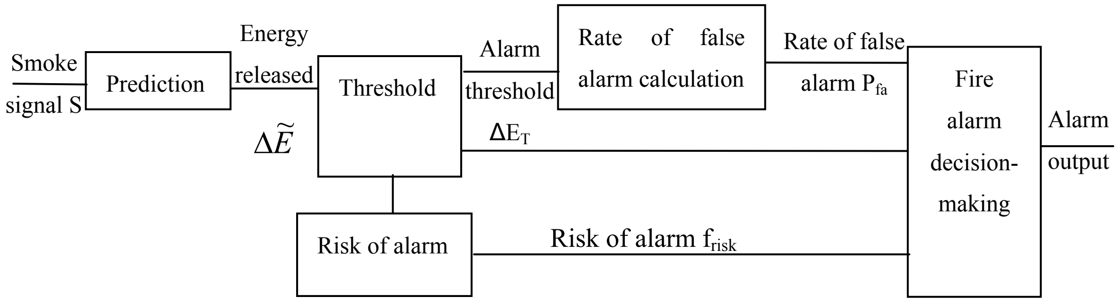

Fig. 3 Block diagram of the algorithm of energy release prediction for smoke detection

Energy release ΔE is, in fact, the area coved by smoke curve. Future part of smoke curve can be predicted on the basis of present part of the curve. A simplest method is straight-line method with a little poor prediction accuracy. The risk of alarm f_{risk} can be set in accordance with the environmental conditions and protection requirements. A preset alarm threshold ΔE_{T0} can be determined by experimental data and experiences. The alarm threshold is then $\Delta E_T = \Delta E_{T0} * f_{risk}$.

A BP neural network trained by the experimental data can be used to fit the probability function $P(\Delta E, x)$. The output of the neural network can directly be defined as P_{fa} and P_E.

For other detection algorithms of smoke detector, P_{fa} and P_E can also be deduced, provided that their equivalent alarm thresholds ΔE_T can be obtained and the equivalent neural network can then be trained. In this way many detection algorithms can be compared each other and examined objectively.

The algorithm related above is still under development. The non-smoke energy release cannot be acquired by smoke detector. Smoke detector is difficult to avoid false alarm by non-fire sources and failure to report the fires that are without smoke (such as TF6).

Therefore, other type sensors (such as temperature sensor) must be combined in fire detector in order to reduce the rate of false alarm and the rate of failure to alert.

4. Conclusions

The application in smoke detector shows that the energy model is suitable for fire detection. The model provides theoretical relation of the rate of false alarm and the rate of failure to alert. Multi-sensor detection technique and multi-criteria data processing can estimate the energy releases more accurately. Reducing the rate of false alarm, in the view of sensor signal and signal processing, is possible by using this energy model and the algorithm of energy release prediction.

References

[1] H. Luck and K.R. Hase, Signal Detection Aspects in Automatic Fire Detection, Fire Safety Journal, 6 (1983), pp.233-240.

[2] Shu Wang and Zheng Dou, Fire Detection and Fire Signal Processing, Publishing House of Huazhong University of Science & Technology, 1998 (in Chinese).

[3] Bukowski, R.W. and Reneke, P.A., New Approaches to the Interpretation of Signal from Fire Sensors, in Proc. Of the 11th Int. Conf. on Fire Detection at the Duisburg University 1999 (AUBE'99), H. Luck ed., pp.11-21.

[4] Gottuk, D.T., Peatross, M.J. etc., Advanced Fire Detection Using Multi-signature Alarm Algorithms, in Proc. Of the 11th Int. Conf. on Fire Detection at the Duisburg University 1999 (AUBE'99), H. Luck ed., pp.237-246.