A Computing Model of Foil-surface-type IR Decoy Radiation Based on Pyrophoric Multi-hole Activated Metal Combustion Model

Biao Wang¹*, Chaozhe Wang¹, Yongjian Yang¹, Jinke Huang¹
¹Air Force Engineering University, Xi’an, China
*Corresponding author: kbdbtgyd@sina.com

Abstract. A computing model of foil-surface-type IR decoy radiation which considers the changes of combustion time, relative air velocity and height of the decoy is established in this paper. The diffusion concentration of oxygen in the pyrophoric multi-hole activated metal is studied firstly. By solving the heat balance equation of foil, the combustion model of foil is established. Based on this, the infrared radiation of a single foil is calculated and verified by comparison with the experimental results. Finally, the infrared radiation characteristics and the infrared image of the whole foil-surface-type IR decoy are obtained. The calculated results are in good agreement with the experimental measurements, so the computing model provides an effective method for predicting the combustion temperature of foil-surface-type IR decoy under high-altitude and high-speed launching conditions.

1. Introduction
The foil-surface-type IR decoy is a new decoy designed for effectively countering imaging IR guidance missiles. It is composed of a launcher and thousands of foils coated with pyrophoric substance. After launched, thousands of foils start diffusing under the force of air flow, meanwhile, the pyrophoric substance start burning to generate large quantities of heat. This kind of decoy can jam the approaching missiles by forming a similar shape and IR characteristic to its carrier through diffusion and combustion.

The theoretical research of foil-surface-type IR decoy can be divided into two aspects: diffusion law and radiation characteristics. Viau C.R[2], proposed to study the radiation characteristics by means of Monte Carlo simulation. Ernst-Christian Koch and his colleges[3][6] also made related research work. Gao Yong, Ye Shuqin, Li Min and others[7][11] studied the formulations of decoy. However, there is still no general calculation model considering the changes of combustion time, relative air velocity and height of the decoy in the calculation of foil-surface-type IR decoy radiation. In this paper, the combustion model of pyrophoric multi-hole activated metal is established. Based on this, the infrared radiation of a single foil is calculated and compared with the experimental results. Finally, the infrared radiation characteristics and the infrared image of the whole foil-surface-type IR decoy are obtained.

2. Foil combustion model
The basic equation of magnesium’s spontaneous combustion reaction is:

$$2\text{Mg} + \text{O}_2 \rightarrow 2\text{MgO} + \Delta H$$

(1)

The energy change in this reaction is $\Delta H = 1202.9\text{kJ/mol}$.

If heat conduction inside the metal is ignored, the energy change of foil is related to 3 variables: the
energy generated by combustion, the heat convection with air, and the heat emitted by thermal radiation. The calculation formula of foil energy change is:

$$\frac{\partial Q_{foil}}{\partial t} = \frac{\partial Q_{Mg}}{\partial t} - \frac{\partial Q_{con}}{\partial t} - \frac{\partial Q_{rad}}{\partial t}$$  \hspace{1cm} (2)

where $Q_{foil}$ is the total heat of foil, $Q_{Mg}$ is the heat generated by combustion, $Q_{con}$ is the heat convection with air, and $Q_{rad}$ is the heat emitted by thermal radiation. According to Stefan-Boltzmann’s law, $Q_{rad}$ is proportional to the fourth power of temperature.

$$\frac{\partial Q_{rad}}{\partial t} = A\sigma(T^4 - T_u^4)$$  \hspace{1cm} (3)

In Eq.(3), $A$ is the superficial area of foil, $\sigma = 5.67 \times 10^{-8} \text{W/(m}^2\text{K}^4)$ is the Stefan-Boltzmann constant, $T$ is the temperature of foil, and $T_u$ is the temperature of surrounding air.

As the foil is flying, the surrounding air is driven to move, and produces amount of internal friction in air because of its viscosity. And the internal fraction heats the surrounding air. The heat convection with air can be described as follows.

$$\frac{\partial Q_{con}}{\partial t} = A h_i (T - T_u)$$  \hspace{1cm} (4)

where $h_i$ is the heat transfer coefficient, which can be calculated from:

$$h_i = 0.332 \sqrt{\frac{\rho V_f}{D_f}} \sqrt{\frac{c_p^2 \lambda_u}{\mu}}$$  \hspace{1cm} (5)

In Eq.(5), $\rho$ is the air density, $V_f$ is the velocity of foil, $D_f$ is the diameter of foil, $c_p$ is the constant pressure specific heat of air, $\lambda_u$ is the heat conduction coefficient, and $\mu$ is the dynamic viscosity coefficient of air.

A sketch map of activated material foil is shown as Fig.1. A surface porous structure is usually adopt in order to increase the contact area between active metal and air.

Suppose the thickness of active metal is $L$ and the number of pores in the surface porous structure is $n$. Experimental analysis shows that the spontaneous combustion rate of Mg is mainly related to environment temperature $T_u$, oxygen concentration $C$, foil velocity $V_f$, and porosity $\omega$. First, calculate the porosity of active metal:

$$\omega = \frac{n D_h^2}{D_f}$$  \hspace{1cm} (6)

where $D_h$ is the pore diameter. Suppose the thickness of active metal at time $t$ is $L(t)$, which can be calculated from:

$$L(t) = L - \frac{LkW_2(t)M_{Mg}}{m}$$  \hspace{1cm} (7)
where $W_{o_2}(t)$ is the total consumption of $O_2$ at time $t$, $m$ is the mass of Mg, $M_{Mg}$ is the molar mass of Mg, and $k$ is the consumption ratio of Mg to $O_2$.

Oxygen in the air reacts with the active metal by diffusing into the porous structure. The diffusion mode includes volume diffusion and volume mass exchange. As the diameter of pore is on the same order of magnitude as the mean free path of diffusion molecular, the oxygen molecules keep colliding with the pore wall in the process of diffusion, which makes the volume diffusion coefficient is very small and the diffusion resistance of oxygen in the pore be very high. Therefore, the concentration of oxygen drops as the diffusion goes deeper, which reduces the reaction speed of spontaneous combustion.

The mass flow rate of $O_2$ per unit area is

$$J_{o_2} = -D \frac{dC}{dz}$$

(8)

where $D$ is the diffusion coefficient of $O_2$, which can be calculated from:

$$D = \frac{1}{6} D_n \left( \frac{RT}{\pi} \right)^{\frac{1}{2}}$$

(9)

The active metal generates amount of heat by reacting with oxygen, meanwhile, its own weight keeps decreasing. So there must be an equilibrium relationship between energy and mass, which is related to oxygen concentration and active metal’s temperature. The equilibrium of oxygen can be described as:

$$\left( 2 \right)^2 \left( \frac{4}{6} \right) \left( k \right) \left( C(z) \right) dC = k, C(z)$$

(10)

where $k$ is the reaction rate constant, and $C(z)$ is the oxygen concentration at depth of $z$, where $z = L(t)$ represents the surface of active metal and $z = 0$ represents the bottom of active metal.

Suppose oxygen in the pore reaches the equilibrium point rapidly, so there’s the following equation:

$$\frac{dC}{dt} = 0$$

(11)

Combine Eq.(10) and Eq.(11):

$$\frac{d^2C}{dz^2} = \frac{4nDk, C(z)}{D_jD}$$

(12)

At the bottom of active metal ($z = 0$), the oxygen concentration and the reaction rate are both the lowest, and there is almost no oxygen flowing in. So one of the boundary conditions is:

$$dC/dz \big|_{z=0} = 0$$

(13)

At the surface of active metal ($z = L(t)$), the oxygen concentration and the reaction rate are both the highest. Oxygen flows into the pore by volume diffusion and volume mass exchange. So the other boundary condition is:

$$D \frac{dC}{dz} \big|_{z=L} = k_m \left( C_{o_2} - C(z) \right)$$

(14)

$k_m$ is the volume mass exchange coefficient, which can be calculated from:

$$\left\{ \begin{array}{l}
k_s = 0.182 \left( \frac{p_0}{p} \right) \left( \frac{T}{T_0} \right)^{1.81} \\
k_m = 0.664 \sqrt{\frac{V_c}{D_j}} \sqrt{\frac{\rho k_s^2}{\mu}}
\end{array} \right.$$

(15)

where $\rho$ is the air density, $\mu$ is the dynamic viscosity coefficient of air, $p_0$ is the standard
atmospheric pressure, and \( T_0 \) is the standard atmospheric temperature.

By integrating Eq.\((12)\), with boundary conditions Eq.\((13)\) and Eq.\((14)\), the oxygen concentration at depth of \( z \) is:

\[
C(z) = \frac{C_{\infty} \operatorname{ch}(\theta z)}{\operatorname{ch}(L(t)\theta) + \frac{D\theta}{k_m} \operatorname{sh}(L(t)\theta)}
\]  \hspace{1cm} (16)

\[
D \frac{dC}{dz} = \int_0^{L(t)} \frac{4nD_j k_j C(z)}{D_j} dz
\]  \hspace{1cm} (17)

where \( \theta \) is:

\[
\theta = \frac{2\sqrt{\ln k_j}}{D_j} \left( \frac{RT}{\pi} \right)^{\frac{1}{4}}
\]  \hspace{1cm} (18)

The heat generated by combustion is:

\[
Q_{m_b} = \Delta H J \rho S
\]  \hspace{1cm} (19)

where \( S \) is the pore area:

\[
S = nL(t)\pi D_h
\]  \hspace{1cm} (20)

Based on the above analysis, the heat balance equation of foil(Eq.\((2)\)) can be expanded as:

\[
\frac{C_{\infty} nL(t) \frac{\partial T}{\partial t}}{L} = nL(t)\pi D_h \int_0^{L(t)} \frac{4\Delta H D_j k_j n C(z)}{D_j} dz - A h_s (T - T_s) - A \varepsilon (T^4 - T_s^4)
\]  \hspace{1cm} (21)

The consumption of oxygen can be calculated from:

\[
\frac{\partial W_{o_2}}{\partial t} = 4nL(t)\pi D_h \int_0^{L(t)} \frac{D_h k_j n C(z)}{D_j} dz
\]  \hspace{1cm} (22)

3. Foil combustion simulation results

Programmatically calculate foil temperature and peak radiation. The foil parameters used for simulation are shown in Tab.1.

| Parameter               | Value      | Unit |
|-------------------------|------------|------|
| Pore diameter, \( D_h \) | 1.24 \times 10^{-4} | m    |
| Foil diameter, \( D_j \) | 0.0465     | m    |
| Rate constant, \( k_j \) | 0.03       | cm/s |
| Emissivity, \( \varepsilon \) | 0.85       |      |
| Activated metal weight, \( m \) | 0.6        | g    |

The peak temperature of foil burning under different relative air velocity and height was calculated by simulation. The results are shown in Fig.2 and Fig.3.
It can be seen from the figure that the peak temperature of foil increases with the increase of air velocity, because the greater the speed, the more oxygen in contact with the foil per unit time, the more intense the combustion reaction. The peak temperature of the foil decreases with height, because the higher the height, the lower the ambient temperature and the lower the oxygen concentration, the slower the combustion reaction.

In order to validate the simulation model, the foil was irradiated with an infrared camera under laboratory conditions, as shown in Fig.4. The results of peak temperature under different airflow are shown in Fig.5. Comparing the results of Fig.5 and Fig.2, it is found that the peak stability of the laboratory measurement is about 80K less than that of the simulation. This is because the measured temperature of the instrument is the converted temperature of the radiation and is derived from the blackbody radiation. In fact, the foil is gray-body, so the actual combustion temperature should be higher than the converted temperature. Assuming that the emissivity of foil is \( \varepsilon = 0.85 \), the error between the measured value and the simulated value does not exceed 10% after the conversion, and the law of the variation with the air velocity is very similar. It can be seen that the established foil combustion model is reasonable.

In the combustion model established in the previous section, the amount of reactants is large enough by default, so the model can only simulate the course of the time when the foil begins to burn to a stable combustion, i.e., the time course of the foil temperature rises from the initial ambient temperature to the peak temperature. However, in fact, the reactants coated on the foil is limited. After a certain period of stable combustion, the combustion reaction will slow down until finished, and the foil has a decreasing time history. Therefore, the variation of the burning temperature of the foil with time can be determined by combining the simulation data and the measured data.

The variation of combustion temperature of the foil under different airflow velocities with time is shown in Fig.6. As can be seen from the figure, the foil typically reaches its peak temperature within 1s. The greater the air velocity, the more oxygen the foil contacts and the shorter the temperature reaches the peak value. The result obtained by test is shown in Fig.7. As can be seen from the figure, the greater the air flow velocity, the shorter the foil ignition time, which is consistent with the simulation results.
Meanwhile, the greater the air flow velocity, the shorter the duration of combustion. This is because the amount of reactants on the foil is constant, the greater the air velocity, the more intense the combustion, the higher the peak temperature, the faster the combustion ends.

Fig.6 Variation of combustion temperature with time under different airflow velocities obtained by simulation

Fig.7 variation of combustion temperature with time under different airflow velocities obtained by test

4. Infrared radiation characteristics of the foil
According to Planck's law, the variation of the radiation intensity in the normal direction of 3μm~5μm with airflow velocity and altitude is obtained from the calculation results in Fig.3, as shown in Fig.8.

Fig.8 Radiation Intensity under different airflow velocities and heights obtained by simulation

According to Stephen Boltzmann's law, the infrared radiation is roughly proportional to the fourth power of the temperature. Therefore, the variation rule of infrared radiation with height and speed of the foil is similar to the change rule of the foil combustion temperature with height and speed. In the case of the same foil speed, as the height increases, the radiation intensity in 3μm~5μm decreases substantially, and the infrared radiation in 12km drops to about half of the radiation on the ground. In 8μm~12μm, the infrared radiation of the foil has a similar variation.

Set the launching platform movement speed of 0.6Ma, launch point height of 3m. Combined with the diffusion simulation model established in Ref.[14], the infrared images of the right side of foil-surface-type IR decoy in 8μm~14μm are shown in Fig.9.
Fig. 9 Infrared images of the right side of foil-surface-type IR decoy in 8μm~14μm

Set the launching platform movement speed of 0.6Ma, launch point height of 3m. The infrared radiation intensity in 3-5μm under different azimuth is calculated. Figure 3.16 and figure 3.17 show the radiation azimuth characteristics in horizontal plane and in vertical plane, respectively. In Figure3.17, 0° stands for the heading of the launching platform and 180° stands for the tail of the launching platform.

As can be seen from the figures, the radiation intensity in each direction of the decoy is similar, and the radiation in the front-back direction is slightly smaller than the up-down direction and the left-right direction. This is because the diffusing area in the front-back direction is smaller than other directions. However, the total radiation area and radiation intensity of decoy in the front-back direction are much larger than those of the aircraft.

Fig.10 the radiation azimuth characteristics in horizontal plane

Fig.11 the radiation azimuth characteristics in vertical plane
5. Conclusion
In this paper, a foil combustion model was established; an infrared image simulation model of foil-surface-type IR decoy was established; and the radiation characteristics of surface-source decoy were analyzed. The core of the foil combustion model is solving the energy balance equation and obtaining the combustion temperature under steady-state conditions. The established energy balance equation takes into account the combustion energy, convective heat transfer energy and environmental radiation energy. The calculated results are in good agreement with the experimental measurements. The main conclusions obtained in this paper are:

(1) The radiation of foil-surface-type IR decoy is mainly concentrated in the mid-wave band, and the infrared radiation of 3-5μm is 2-3 times of the infrared radiation of 8-14μm. The ignition time of foil-surface-type IR decoy is about 0.5s, and the burning duration is about 1.5s.

(2) The infrared radiation intensity in all directions of the decoy is not much different, and the infrared radiation in the front-back direction is slightly less than the up-down direction and the left-right direction. The total radiation intensity of decoy decreases with the increase of launching velocity and also decreases with the increase of launching height.

References
[1] Jia Lintong, Tong Zhongxiang, Wang Chaozhe, et al. Survey on airborne surface-type infrared decoy[J]. Infrared and Laser Engineering, 2016,45(9).
[2] Ernst-Christian Koch, Axel Dochnahl. IR emission behavior of Magnesium Teflon Viton (MTV) compositions[J]. Propellants, Explosives, Pyrotechnics, 2000, 25(37): 37-40.
[3] Viau C R. Expendable countermeasure effectiveness against imaging infrared guided threats [C]//ECWI, Second International Conference on Electronic Warfare, 2012.
[4] Ernst-Christian Koch, Axel Dochnahl. IR emission behavior of Magnesium Teflon Viton (MTV) compositions[J]. Propellants, Explosives, Pyrotechnics, 2000, 25(37): 37-40.
[5] Ernst-Christian Koch. Pyrotechnic Countermeasures: II. Advanced Aerial Infrared Countermeasures [J]. Propellants, Explosives, Pyrotechnics, 2006, 31(1): 3-19.
[6] Ernst-Christian Koch. Annual Review on Aerial Infrared Decoy Flares[J]. Propellants Explos.Pyrotech,2009 (34):6-12
[7] Gao Yong. Composite Technology Research of Foil Type Infrared Decoy and Carbon Fiber[D]. Nanjing University of Science and Technology, 2016.
[8] Ye Shuqin, Zhu Chenguang, Lin Hongxue, et al. Study on performance improvement of PTFE/Mg-film infrared decoy burning at low temperature[J]. Infrared and Laser Engineering, 2017, 46(1).
[9] Lin Hongxue, Zhu Chenguang, Li Min, Wang Haizhen. Performance of radiation on film-type infrared flare with low-temperature combustion[J]. Infrared and Laser Engineering, 2014, 43(10).
[10] Yang Chunling, Zhang Zhendong, Liu Guoqiang. Influence of particle radius of composition on radiation characteristics of infrared decoy[J]. Infrared and Laser Engineering, 2016, 45(1).
[11] Li Min. Study of Adhesive Composite of Array Infrared Decoy and Infrared Performance [D]. Nanjing University of Science and Technology, 2013.
[12] Yan Chuan-jun, Fan Wei. Combustion Science[M]. Xi’an: Northwestern Polytechnical University Press, 2015.9.
[13] Caroline K.W. Combustion model for pyrophoric metal foils [J]. Propellants, Explosives, Pyrotechnics, 2003,28(6):296-300.
[14] ZOU Tao, WANG Chaozhe, TONG Zhongxiang. Diffusion rule of foil-surface-type infrared decoy[J]. Acta Aeronautica et Astronautica Sinica, 2016,37(9):2634-2645.