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Measurement of Infrared Transmissivity of Smoke Using a Thermal Imager

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ABSTRACT

The smoke is an effective camouflage method and is widely used in the modern battlefields. The smoke chamber test is used quantitatively to extinct the energies of the smoke material. In the smoke chamber test, a key problem is to accurately measure the transmissivity of the smoke. In this paper, the relationship between the temperatures measured and the radiation received by the thermal imager has been disussed. The equation to accurately calculate the infrared transmissivity of the smoke from the measured temperature is deduced. This equation is also compared with the simplified one.

Keywords: Smoke chamber test, thermal imager, extinction characteristic, smoke transmission infrared transmissivity of smoke, smoke material

1. INTRODUCTION

The smoke plays an important role in the modern battlefields. It is often used to extinct the energies from the target, which could be received by detectors of the hostile electrooptical guided weapons so as to protect the target from these weapons[1]. The infrared transmissivity of the smoke has intense effect on its performance. So, it is of practical significance to precisely measure it. The measurement of infrared transmissivity of the smoke can be done by the field test and the laboratory test. The field test is usually employed to evaluate the overall performance of the smoke chamber, while the laboratory test is mainly used to assess the characteristic of the smoke material. The laboratory test can be carried out in a smoke chamber using a thermal imager. By recording the temperature displayed by the thermal imager, the infrared transmissivity of the smoke can be deduced[2,3].

The smoke chamber itself affects the energy received by the thermal imager, and thus affects the measured temperature. These effects have to be eliminated to accurately obtain the infrared transmissivity of the smoke.

This paper deals with the accurate measurement of the infrared transmissivity of the smoke by eliminating the effect of the smoke chamber.

2. EXPERIMENTAL SETUP

Assuming that there is a radiant source (ie, an object) with radiance (L_0). After the extinction by the smoke, the radiance becomes L_1 (Fig. 1). Then the infrared transmissivity of the smoke is defined as

$$\tau = \frac{L_1}{L_0} \qquad (1)$$

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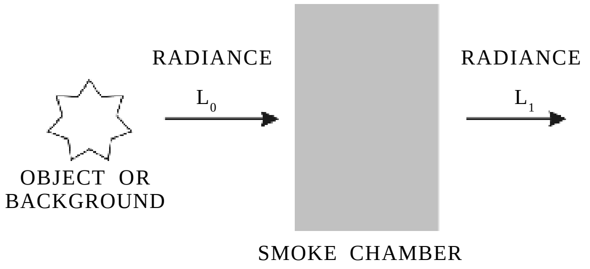


Figure 1. Schematic of testing the infared transmissivity of the smoke.

In practice, the smoke is usually confirmed in a chamber to get its volume (Fig. 2). In the meantime, the chamber affects radiation arriving at the receiver. For instance, the reflection and the radiation of the chamber wall (which is relatively transparent to the infrared radiation) make it difficult to accurately get L_1. So, an alternative approach has to be found.

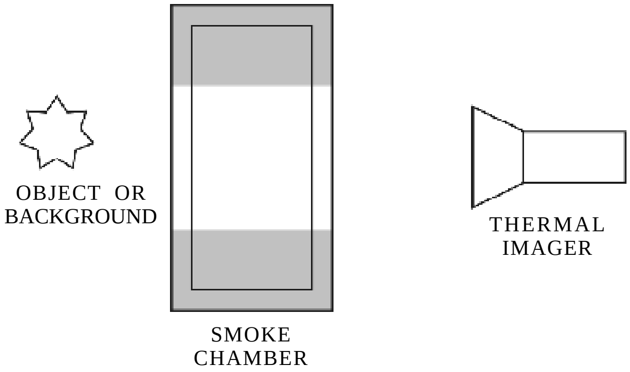


Figure 2. Schematic of the experimental setup.

3. PRINCIPLES OF MEASUREMENT

3.1 Temperature Measurement–Principle of Thermal Imager

To accurately obtain the expression of the transmissivity of the smoke, the principle of temperature measurement of thermal imager has been discussed here.

Assuming that there is an object in the field of view of the thermal imager. It will cast an image on the detector. The brightness of the image is determined by the received radiant flux. According to this radiant flux and the infrared emissivity, the actual temperature of the object can be accurately calculated[4,5].

The radiant flux (Φ) of the object in the band $\lambda_1 \sim \lambda_2$ reaching the pupil of the thermal imager can be expressed as

$$\Phi = EA \tag{2}$$

where E is the radiant illumination of the object on the pupil with an area (A).

Assuming that the temperature and the radiant emittance of the object are T and $M(T)$, respectively. If the object is a diffusing radiator located at the centre of the field of view, then

$$E = \frac{M(T)\Delta\Omega}{\pi} \tag{3}$$

where $M(T)$ is defined as the radiant flux which a radiant point radiates in the direction of the hemispherical space and $\Delta\Omega$ is the solid angle of the object to the thermal imager (Fig. 3).

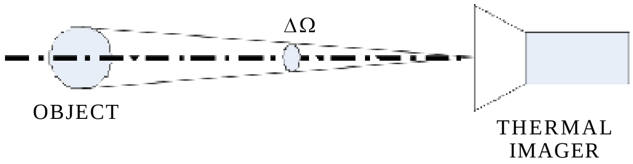


Figure 3. Schematic of the radiant flux received by the detector.

Assuming that the emissivity of the object is ε, Eqn (3) can be rewritten as

$$E = \frac{\varepsilon M_b(T)\Delta\Omega}{\pi} \tag{4}$$

where $M_b(T)$ is the radiant emittance of the blackbody given by

$$M_b(T) = \int_{\lambda_1}^{\lambda_2} M_{\lambda b}(T)\, d\lambda = \int_{\lambda_1}^{\lambda_2} \frac{c_1}{\lambda^5} \frac{1}{e^{c_2 \lambda T} - 1} d\lambda \tag{5}$$

where $c_1 = 3.741832 \times 10^{-16}\ Wm^2$ and $c_2 = 1.438786 \times 10^{-2}\ mK$. It should be pointed out that there is a one-to-one correspondence between $M_b(T)$ and T. In other words, there is only one $M_b(T)$ corresponding to a given T, and vice versa. Figure 4 shows the relationship between the radiant emittance and the temperature of the blackbody, where the areas of

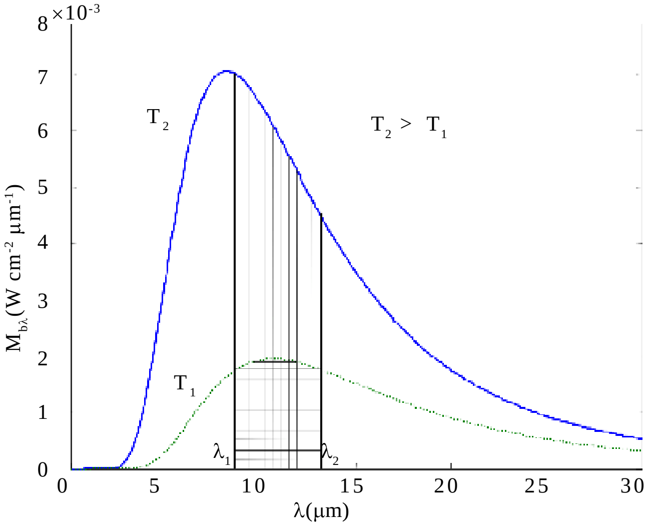


Figure 4. **Relationship between the radiant emittance and the temperature of the blackbody.**

the dotted regions represent the values of $M_b(T)_s$. Obviously, one can get the temperature of the object from its radiant emittance.

3.2 Expression of Infrared Transmissivity for the Smoke Chamber Measurement

For an empty chamber, ie, there is no smoke in it, the overall radiant flux (Φ) received by the thermal imager (Fig. 5) can be written as

$$\Phi = \Phi_1 + \Phi_2 + \Phi_3 + \Phi_4 \qquad (6)$$

where Φ_1 is the radiant flux attenuated by the smoke and the films 1 and 2 from the object, Φ_2 is the one of the film 1, Φ_3 is the one attenuated by the smoke and the film 1 from the film 2, and Φ_4 is the radiant flux reflected by the film 1 from the surroundings. Based on Eqn (2), Eqn (6) can be changed into

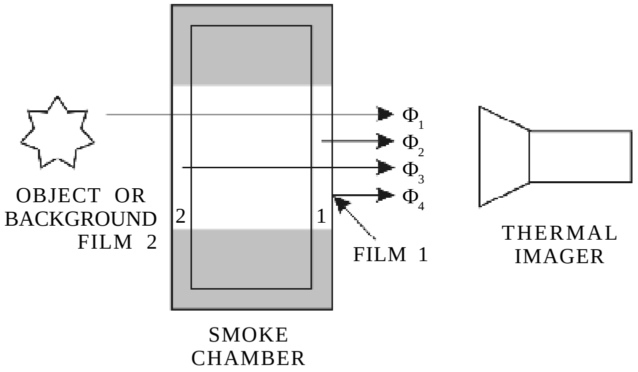


Figure 5. **Radiant flux received by the thermal imager from an empty smoke chamber.**

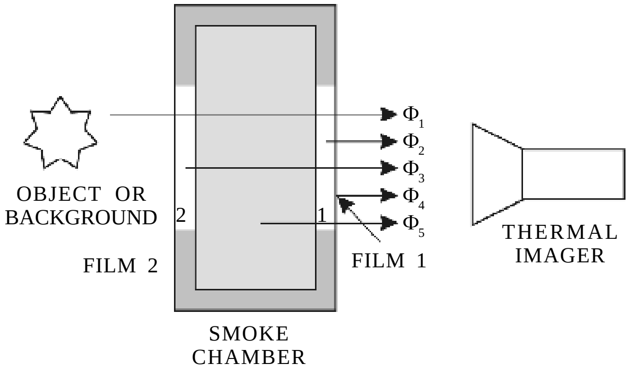


Figure 6. **Radiant flux received by the thermal imager for a chamber filled with smoke.**

$$E = E_1 + E_2 + E_3 + E_4 \qquad (7)$$

where E, E_1, E_2, E_3 and E_4 are the corresponding radiant illumination of the radiant fluxes in Eqn (6), respectively. Then the apparent radiant emittance of the object is given by

$$M_m = M(T_{obj})\tau^2_f + M_{f,ra} + M_{f,ra}\tau_f + M_{f,re} \qquad (8)$$

where $M(T_{obj})$ is the radiant emittance of the object with temperature T_{obj}, $M_{f,ra}$ *and* $M_{f,re}$ are the radiant emittance and the reflection, respectively of the film, and τ_f is the transmissivity of a single film.

Similarly, if a point is selected in the background, then the apparent radiant emittance of it is:

$$M_b = M(T_{back})\tau^2_f + M_{f,ra} + M_{f,ra}\tau_f + M_{f,re} \qquad (9)$$

where $M(T_{back})$ is the radiant emittance of the background with the temperature T_{back}.

Figure 6 illustrates the radiant flux received by the thermal imager from the test chamber filled with smoke. Φ_5 is the radiant flux attenuated by the film 1 from the smoke itself. Φ_2 and Φ_4 are the same as those in Fig. 5. Hence, in this case, similar to the above deduction, the apparent radiant emittances of the object and the background are:

$$M_c = \tau M(T_{obj})\tau^2_f + M_{f,ra} + M_{f,ra}\tau\tau_f + M_{f,re} + M_{s,ra}\tau_f \qquad (10)$$

$$M_h = \tau M(T_{back})\tau_f^2 + M_{f,ra} + M_{f,ra}\tau\tau_f + M_{f,re} + M_{s,ra}\tau_f \tag{11}$$

where τ is the transmissivity of the smoke and $M_{s,ra}$ is its radiant emittance.

From Eqns (8)–(11), the infrared transmissivity of the smoke is given by

$$\tau = \frac{M_c - M_h}{M_m - M_b} \tag{12}$$

The parameter the thermal imager can give is the temperature. If the radiant emissivity is known and input into the thermal imager, the temperature measured is the actual one, ie, T. However, if the emissivity is set to be 1, the temperature shown by the thermal imager is an apparent temperature (T_a). That is, the apparent radiant emittance can be given by

$$M = \varepsilon M_b(T) = M_b(T_a)$$

Let the radiant emissivity be 1, then Eqn (12) can be rewritten as

$$\tau = \frac{M_b(T_c) - M_b(T_h)}{M_b(T_m) - M_b(T_b)} \tag{13}$$

where T_c and T_h are the apparent temperatures of the object and the background, respectively when the smoke chamber is filled with the smoke, T_m and T_b are the apparent temperatures of the object and the background, respectively for an empty smoke chamber. All these temperatures can be attained by the thermal imager. So, using Eqn (13), one can easily get the transmissivity of the smoke.

4. DISCUSSION

Since the effect of the film is eliminated, Eqn (13) can accurately calculate the transmissivity of the smoke. If the temperatures of the object are far more greater than those of the background, that is, $M_b(T_c) >> M_b(T_h)$ and $M_b(T_m) >> M_b(T_b)$, Eqn (13) can be simplified to

$$\tau = \frac{M_b(T_c)}{M_b(T_m)} \tag{14}$$

This is an approximate equation someone tends to use. To discuss the difference between Eqns (13) and (14), let one assume that T_m = 50 °C, T_c =30 °C, and T_b=30 °C, the transmissivities of the smoke calculated by the above two equations are shown in Fig. 7. In this figure, the band is chosen to be 8µm~14µ*m*. The temperature of the background when the smoke chamber is filled with the smoke, T_h, is set to change from 20 °C to 30 °C.

From Fig. 7, one can find that the transmissivity calculated by Eqn (14) is greater than that given Eqn (13). That is to say, the simplified equation overestimates the transmissivity of the smoke. The smaller the value of T_h, the lesser the difference between the transmissivities of the smoke calculated by the two equations. This is consistent with the above analysis. Figure 7 depicts that Eqn (14), as a simplified expression, should be used with caution.

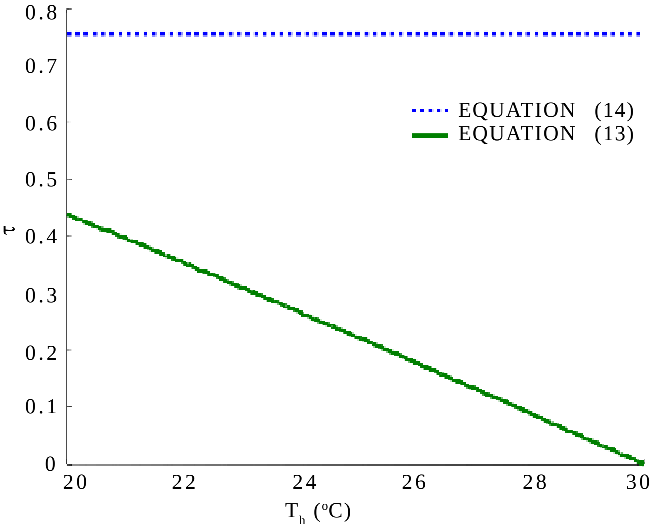


Figure 7. Transmissivities of the smoke calculated from two different equations.

5. EXPERIMENTAL PROCEDURE

The difference between Eqns (13) and (14) has been demonstrated by means of the experiment.

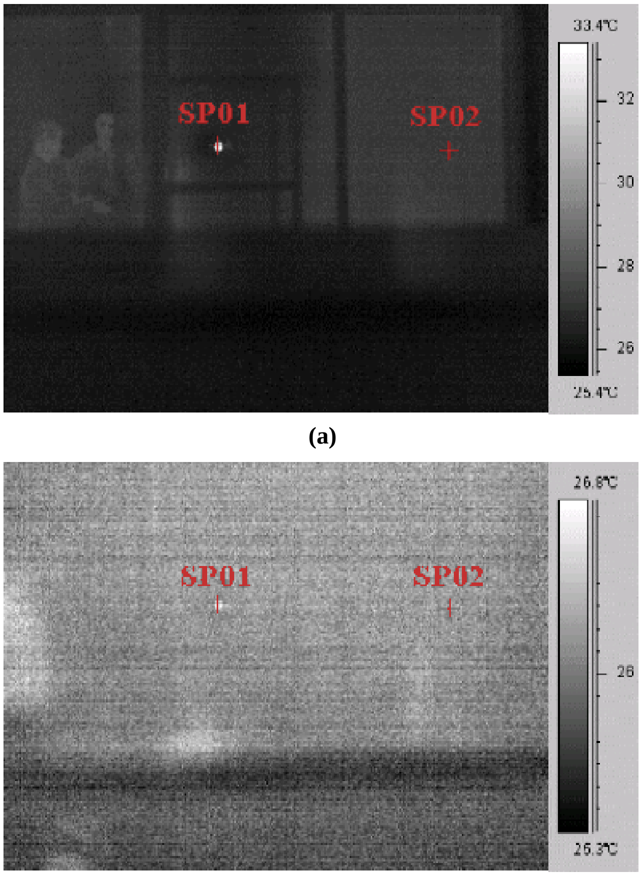
The experimental setup is shown in Fig. 2. The thermal imager works in the band of 7.5 µ*m* ~ 13 µ*m* and the sensitivity is < 1 °C. A blackbody acts as an object. A certain point in the environment is selected as the background. The thermal imager is initialised so that both the radiant emissivities of the object and the background have the value of 1.

In the experiment, the smoke material is blown into the smoke chamber and disseminates in the chamber. The thermal imager simultaneously records the infrared imagers. Figure 8 gives the infrared images of the initial state and 10th second after the blow of the smoke into the smoke chamber. The temperatures of the object and the background can be read according to these images. The infrared transmissivities of the smoke can also be calculated. The data are listed in Table 1.

Based on the calculated results, it is observed that there is a large difference in the values of the smoke transmissivity (τ) when calculated using Eqns (13) and (14). It is indicated that when measuring the infrared transmissivity of the smoke using a thermal imager, Eqn (13) is preferable to Eqn (14).

Table 1. Temperatures and calculated transmissivities

Temperature				**The transmissivity calculated by**	
(T_m)	**(T_c)**	**(T_b)**	**(T_h)**		
(°C)	**(°C)**	**(°C)**	**(°C)**	**Eqn (13)**	**Eqn (14)**
49.7	28.2	27.1	26.5	0.0675	0.7235



(a)

(b)

Figure 8. Infrared images recorded by the thermal imager: (a) image of the initiated state and (b) image at 10th second after the blow of the smoke into the smoke chamber. (SP01 is the point of the object and SP02 is the point of the blackbody).

6. CONCLUSIONS

The infrared transmissivity of the smoke is a key parameter in evaluating the extinction characteristic of the smoke material. In the laboratory, transmissivity is usually measured using a smoke chamber and a thermal imager. This paper introduces an easy and useful method to eliminate the negative effect of the chamber wall and to accurately obtain the transmissivity of the smoke. Numerical calculations demonstrate that the simplified equation is only valid in specific situations.

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