

## Laboratory assessment of thermal transmission in camouflage materials using the SR-5000N spectroradiometer

Tran Tien Bao, Nguyen Anh Tuan\*

Institute of Technical Physics, Academy of Military Science and Technology, 17 Hoang Sam, Cau Giay, Hanoi, Vietnam.

\*Corresponding author: tuanvn.vn@gmail.com

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### ABSTRACT

*Recent domestic research on camouflage requires standardized evaluation methods and techniques to scientifically and reliably assess camouflage materials, such as fabrics and camouflage nets. This poses significant challenges due to the high level of confidentiality in the field and the limitations of experimental equipment. Drawing on several standards published by advanced nations, this study proposes a method for determining the thermal radiation transmission ratio through camouflage materials in a laboratory setting using the SR-5000N device. The proposed method offers several advantages, including rapid execution, accuracy, reliability, and broad spectral coverage, encompassing the two primary spectral regions of thermal camouflage: the mid-wave infrared (MWIR) and the long-wave infrared (LWIR) ranges. Independent field evaluations have validated the method's effectiveness, demonstrating its practicality in saving time and resources for assessing the performance of thermal camouflage.*

**Keywords:** Thermal camouflage; Thermal signature; Emissivity; Thermal transmission; SR-5000N spectroradiometer.

### 1. INTRODUCTION

In recent years, research on thermal camouflage has emerged as a topic of significant interest among scholars worldwide. Publications in this field are predominantly authored by research groups such as TNO from European countries, as well as scientists from China, India, South Korea, ... [1, 2]. This underscores the fascinating nature of this domain, which offers numerous avenues for exploration and a plethora of scientific challenges to address. These can be broadly categorized into two main areas: first, the development of techniques and technologies for thermal camouflage, and second, the evaluation methods to assess the effectiveness of such camouflage. Some studies have extended the spectral range to encompass multispectral camouflage. Nevertheless, thermal camouflage remains a central focus and an indispensable component of multispectral camouflage [1-3].

Domestically, research on camouflage has been increasingly prioritized over the past decade, achieving several notable and encouraging outcomes. To date, domestic studies have primarily focused on the first area, with an emphasis on developing material technologies and physical solutions for producing effective thermal camouflage equipment for soldiers and certain military vehicles. These efforts aim to reduce the likelihood of detection and observation by thermal imaging devices. Broadly speaking, thermal imaging devices operate on the principle of capturing thermal radiation emitted by a target, converting it into electrical signals, and displaying a pseudo-temperature field on a screen. This enables thermal images of objects to be observed both during the day and at night [4-6]. Thermal camouflage, therefore, involves addressing the challenge of eliminating or minimizing the thermal signature of an object. This entails reducing the thermal contrast (temperature difference) between the target and its background or, in other words, adjusting the target's thermal radiation to resemble or approximate that of the background. Based on the operating principles of thermal imaging devices and Stefan-Boltzmann's law, the thermal signature of an object is a function of its surface temperature  $T$  and emissivity coefficient  $\varepsilon$  [8, 9].

From this, two fundamental strategies for thermal camouflage can be identified: altering the local surface temperature ( $T$ ) of the object or modifying the local emissivity coefficient ( $\epsilon$ ) of the target [8-11]. Corresponding to these strategies, the principles of thermal camouflage are termed thermal conduction camouflage techniques and thermal emission camouflage techniques, respectively [12-19]. Consequently, thermal camouflage solutions are developed around technological approaches to fabricating materials with low emissivity coefficients, as well as insulating, shielding, and heat-absorbing properties. These methods aim to reduce the intensity of thermal radiation emitted by the target, thereby enhancing the effectiveness of thermal camouflage.

For the technological solution of fabricating materials with low emissivity coefficients, the thermal camouflage materials are evaluated by measuring their surface emissivity. This involves comparing the measured emissivity values with the required emissivity range necessary to achieve effective thermal camouflage. Numerous methods for measuring the surface emissivity of materials have been studied and published, employing various measurement techniques [20-22]. The research team has published a method for measuring the surface emissivity of camouflage materials using the SR-5000N spectroradiometer [20].

For the technological solution involving the fabrication of materials with thermal insulation and shielding properties, the evaluation of camouflage effectiveness based on this approach still lacks an established formal standard [23-25]. This presents challenges for domestic scholars in identifying reliable scientific criteria to assess the thermal insulation and shielding capabilities of thermal camouflage materials. Consequently, there is a pressing need to develop and establish a reliable evaluation method to support research efforts in thermal camouflage.

In this context, we propose a method for determining the thermal transmission coefficient of thermal camouflage materials based on spectral radiation data measured using the SR-5000N spectroradiometer. The proposed method offers several advantages over previously published approaches, including high accuracy due to the device's high sensitivity and wide measurement range (2.39-14.34  $\mu\text{m}$ ). This allows for the determination of the thermal transmission across key spectral ranges to be relevant to thermal camouflage, namely the mid-wave infrared (MWIR) range (3-5  $\mu\text{m}$ ), the long-wave infrared (LWIR) range (8-14  $\mu\text{m}$ ), and the full spectrum.

The paper is organized into four sections: Section 1 introduces the topic, section 2 presents the theoretical foundation of the thermal transmission concept, section 3 details the experimental results for calculating the thermal transmission coefficient using the SR-5000N device, and section 4 provides the conclusion.

## 2. THE THERMAL TRANSMISSION CONCEPT AND PROPOSED METHOD

This section outlines the theoretical foundation of thermal transmission. Objects above absolute zero emit thermal radiation, creating thermal signatures when uncovered areas have apparent temperatures differing from the surroundings. Thermal reconnaissance devices detect these signatures to identify objects. Camouflage coverings, such as nets or garments, are essential for reducing thermal contrast and detection risks. Their thermal transmission properties depend on material coverage, with different materials offering varying degrees of effectiveness within the thermal domain.

### 2.1. Thermal suppression

In general, thermal suppression is a parameter used to evaluate the heat-shielding capability of camouflage materials, based on surface temperature data as proposed by O. Dev et al. [11]. The greater the thermal suppression, the higher the material's ability to block heat, resulting in more effective thermal camouflage, and vice versa. Thermal suppression measurements of camouflage materials were conducted using a PID-controlled Acmas hot plate (temperature range from room temperature to 350 °C with an accuracy of 1 °C) as the heat source and a FLIR thermal imaging

system (model SC7900VL, equipped with 12 mm optics and a wavelength range of 7.7-11.5  $\mu\text{m}$ ). The irradiance on the camera is higher in the LWIR range (8-12  $\mu\text{m}$ ), reducing the signal-to-noise ratio (SNR) for objects with temperatures close to the background, but improving as the source temperature increases. In this measurement, the source temperature was higher than the background temperature. The average temperatures of the background, source, and camouflage material were derived from the irradiance on the camera using the following equation [11]:

$$\left( \int_{\lambda_1}^{\lambda_2} \frac{C_1}{\lambda^5 \left( \varepsilon \frac{C_2}{\lambda T} - 1 \right)} d\lambda \right)^{object} = \frac{1}{\varepsilon} \left( W_{\lambda_1, \lambda_2}^{total} - (1 - \varepsilon) W_{\lambda_1, \lambda_2}^{reflected} \right) \quad (1)$$

where  $\lambda_1, \lambda_2$  are wavelengths,  $C_1, C_2$  are constants,  $T$  is temperature of object,  $\varepsilon$  is emissivity of object,  $W^{total}$  is total received power and  $W^{reflected}$  is reflected power from the ambient sources.

Measurements have been carried out at 50, 100 and 150  $^{\circ}\text{C}$  in present study and camouflage material were placed at stand-off distance 8, 16 and 24 mm from hot plate. The schematic diagram of thermal suppression measurement set up is shown in the figure 1 [11].

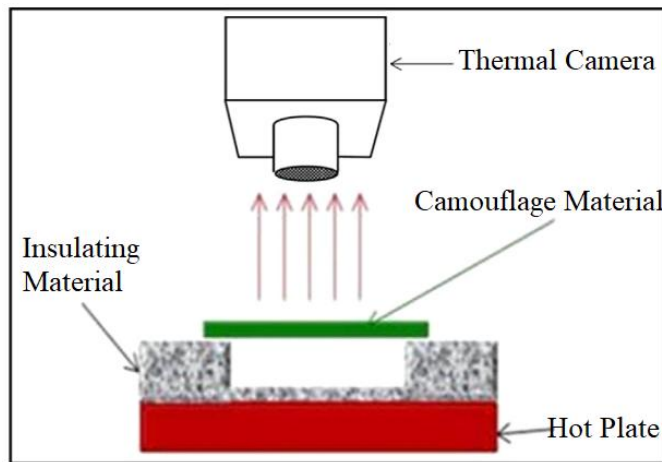


Figure 1. Diagram of the test setup for thermal suppression measurement [11].

Thermal suppression efficiency offered by camouflage material has been calculated using following equation [11]:

$$T_s (\%) = \frac{T_{HP} - T_{CM}}{T_{HP} - T_{BG}} \times 100 \quad (2)$$

where,  $T_{HP}, T_{BG}, T_{CM}$  represent, respectively, the temperature of the heating plate, the ambient temperature, and the surface temperature of the camouflage material in a steady-state condition.

## 2.2. Thermal transmission

In contrast to thermal suppression, thermal transmission evaluates the heat transfer through camouflage materials based on the thermal radiation energy measured using radiometric devices [23-25]. Thus, the smaller the thermal transmission, the greater the ability to block heat transfer, indicating better thermal camouflage effectiveness, and vice versa.

The test setup is configured as shown in figure 2. A blackbody system with a 20 cm  $\times$  20 cm active area is used to simulate the target. The thermal camera is positioned 2 meters in front of the camouflage sample holder to capture a large image of the blackbody emitter area while ensuring a well-focused image at the level of the camouflage sample. The blackbody emitter is placed at distances of 0.5 m, 1 m, and 1.5 m behind the camouflage material (figure 2). Thermal scenes are recorded using the camera's software. Recordings are set to 100 frames in length and are conducted

first for a bare target (no camouflage material) and then for the camouflaged target. The recorded data are subsequently analyzed using thermographic analysis software. For each recording, the temporal mean values (over the 100 frames) of the spatial mean values (within the defined region of interest) are calculated in terms of temperature, radiance, and count (gray level) units.

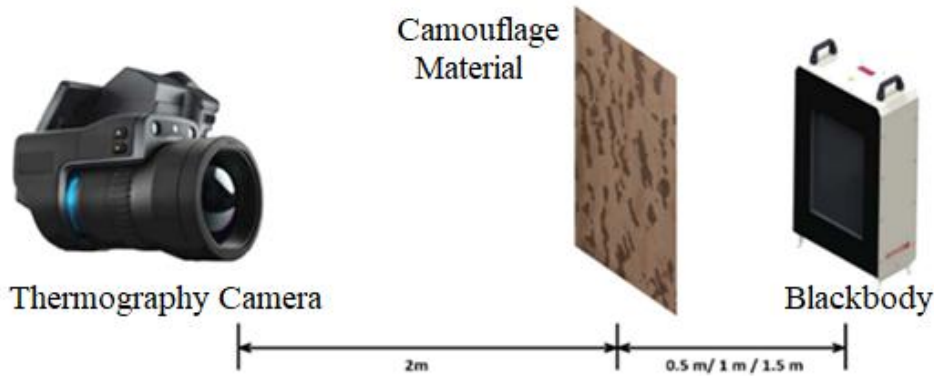


Figure 2. Diagram of the test setup for thermal transmission measurement [25].

The percentage camouflage material thermal transmission is calculated using the mean radiance values, with and without the camouflage material as shown in the equation below [25]:

$$T_T(\%) = \frac{R_{CM,60} - R_{CM,45}}{R_{BB,60} - R_{BB,45}} \times 100 \quad (3)$$

where,  $R_{CM,60}$  and  $R_{CM,45}$  represent the recorded radiation from camouflaged target, the blackbody set at 60 °C and 45 °C, respectively.  $R_{BB,60}$  and  $R_{BB,45}$  represent the radiation from the bare target, the blackbody set at 60 °C and 45 °C, respectively.

According to equation 2, thermal transmission  $T_T(\%)$  may be calculated in the same way for different target temperatures and temperature spans. However, according to the results published by R. Karli et al. [25], for thermal camouflage materials,  $T$  is always below 25%.

### 2.3. Requirement of thermal transmission of Multispectral Lightweight Camouflage Net (MLCN)

Thermal transmission has been referenced in the technical specifications for thermal camouflage in Sweden's Multispectral Lightweight Camouflage Net (section 3.3.1.1), as illustrated in figure 3 [23]. According to these specifications, the thermal transmission coefficient (calculated using equation (2), with room temperature around 22 °C and the camouflage net positioned approximately 1.5 m from the target) of the MLCN camouflage net must not exceed 25% in both the 3-5  $\mu\text{m}$  and 8-12  $\mu\text{m}$  spectral ranges [23].

 	<b>Multispectral Lightweight Camouflage Net 2015 – MLCN</b>	
	Document identity	Version
	Enclosure 1 to Enquiry 366823-AI854206 – Technical Specification	Page A 7 (25)

### 3.3 THERMAL INFRARED (TIR) SIGNATURE

Applies to final MLCN units.

#### 3.3.1 Requirement, thermal transmission

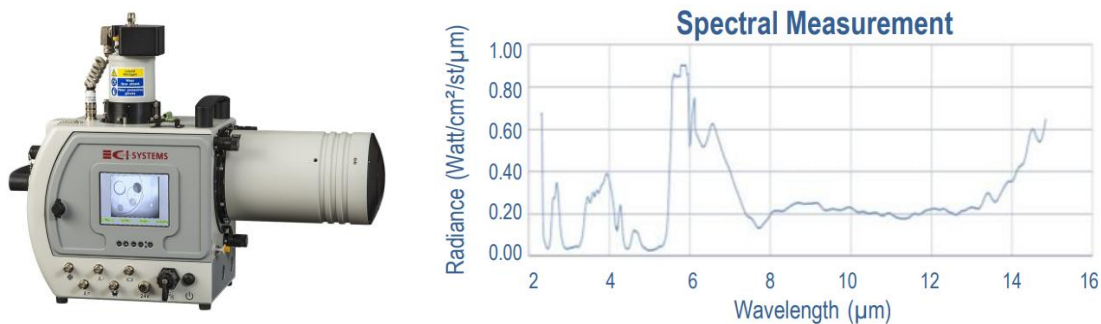
The thermal transmission is a measure of how much a hot surface is seen through a camouflage net.

3.3.1.1 The thermal transmission of MLCN shall be maximum 25% in wavelength regions 3-5  $\mu\text{m}$  and 8-12  $\mu\text{m}$ .

Figure 3. Requirement of thermal transmission of MLCN [23].

## 2.4. Proposed thermal transmission measurement using SR-5000N

The Spectroradiometer (SR-5000N) is an instrument designed to investigate radiation-emitting objects, covering the entire spectral range from UV to IR, as shown in figure 4 [20]. The SR-5000N measures the emitted spectral radiance of any object in its field of view in absolute units of [Watts/(sr.cm<sup>2</sup>.μm)]. It is used in a wide variety of scientific, military and industrial applications that demand real-time, highly accurate and highly sensitive measurements.



**Figure 4.** The SR-5000N spectroradiometer and the spectral measurement [20].

Based on the studies presented in sections 2.1, 2.2, and 2.3, the effectiveness of thermal camouflage materials in shielding and blocking thermal radiation, reducing transmission to thermal imaging receivers, and filtering out object thermal signatures is assessed as follows:

For thermal suppression, it is evident that this parameter is derived from the apparent temperatures of the components, which are calculated using equation (2). The apparent temperature may differ from the actual temperature if the surface emissivity coefficient is not precisely known, as indicated by Stefan-Boltzmann's law [2]. Therefore, the effectiveness of thermal camouflage should be evaluated in terms of the reduction in the target's radiative energy rather than solely focusing on the decrease in the surface temperature of the object.

Both studies [23] and [25] use equation (3) to calculate the spectral radiance of camouflaged and non-camouflaged objects, demonstrating that a thermal transmission value below 25% ensures effective camouflage. However, as figure 2 highlights, measuring across multiple spectral bands with thermal cameras poses challenges, potentially leading to incomplete evaluations. To address this, the authors propose a reliable and effective method for measuring the thermal transmission of camouflage materials using the SR-5000N spectroradiometer, as detailed below:

- Replace the thermal camera in figure 2 with the SR-5000N spectroradiometer;
- Position the thermal camouflage material at a distance of 0.5 meters from the target, and the SR-5000N device at a distance of 5 meters from the target;
- Calculate the thermal transmission in the MWIR and LWIR ranges using equation (3);
- For thermal camouflage materials, the thermal transmission in both spectral ranges (MWIR and LWIR) must not exceed 25% (this serves as an evaluation criterion).

## 3. EXPERIMENT AND DISCUSSION

In this section, to clarify the reliability of thermal transmission measurements in laboratory conditions and the significance of establishing a reliable laboratory measurement method for evaluating camouflage materials prior to conducting field tests, the research team selected four samples of thermal camouflage materials for soldiers for experimentation. The experiment was divided into two steps: the first step involved measuring the thermal transmission in the laboratory, and the second step focused on field evaluation. The implementation steps, results, and discussions are presented as follows:

### 3.1. Experimental setup

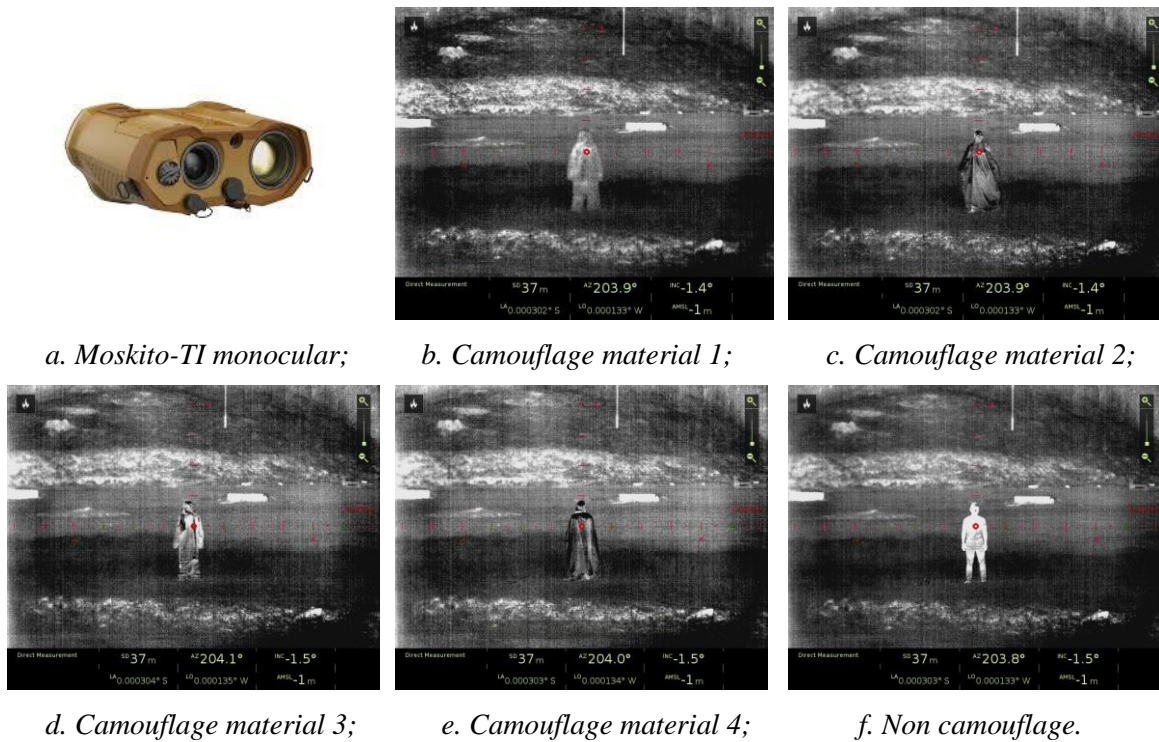
#### 3.1.1. Measuring thermal transmission with SR-5000N

According to the proposed method for measuring thermal transmission, the experimental setup is arranged as shown in figure 2, utilizing the SR-5000N in place of a thermal camera.

Sequentially hang the thermal camouflage material samples (CM) listed from 1 to 4 in table 1, and operate the SR-5000N device software to measure the spectral radiance in the 3-5  $\mu\text{m}$  and 8-14  $\mu\text{m}$  spectral ranges. Use equation (3) to calculate the thermal transmission for each sample.

#### 3.1.2. Field testing to assess camouflage effectiveness

Wear the thermal camouflage outfits and observe and capture images of the outfits in the field using the Moskito-TI thermal monocular from a distance of approximately 40 m. The monocular features an uncooled sensor with a resolution of 640x480 pixels, a spectral range of 8–14  $\mu\text{m}$ , and a thermal sensitivity (NETD) of less than 50 mK, as illustrated in figure 5. The field tests were conducted after 7 PM at a training ground with low vegetation.



**Figure 5.** Thermal images of the camouflage and non-camouflage targets.

### 3.2. Results and discussion

Following the experimental setup presented in section 3.1.1, the spectral radiance values (averaged over three measurements) and the corresponding thermal transmission were obtained, as summarized in the table 1.

According to table 1, in the MWIR spectral range, the thermal transmission of the materials, in ascending order, is CM4, CM1, CM3, and CM2. Similarly, in the LWIR spectral range, the results follow the same order: CM4, CM1, CM3, and CM2. Thus, across both spectral ranges, the thermal transmission of the materials is ranked as CM4, CM1, CM3, and CM2, with CM4 showing the lowest thermal transmission values, specifically 10.33% in the MWIR range and 18.9% in the LWIR range. These findings indicate that CM4 offers the most effective thermal camouflage performance among the tested materials.

**Table 1.** Spectral radiance and thermal transmission of camouflage materials.

	Spectral band 3-5 $\mu\text{m}$ [Watts/(sr.cm <sup>2</sup> )]					Spectral band 8-14 $\mu\text{m}$ [Watts/(sr.cm <sup>2</sup> )]				
	R <sub>CM,45</sub>	R <sub>CM,60</sub>	R <sub>BB,45</sub>	R <sub>BB,60</sub>	T <sub>T</sub> (%)	R <sub>CM,45</sub>	R <sub>CM,60</sub>	R <sub>BB,45</sub>	R <sub>BB,60</sub>	T <sub>T</sub> (%)
<b>CM1</b>	2.12E-04	2.54E-04	2.64E-04	5.27E-04	<b>16.18</b>	5.94E-03	6.54E-03	6.42E-03	8.54E-03	28.00
<b>CM2</b>	2.24E-04	2.73E-04	2.64E-04	5.27E-04	<b>18.41</b>	5.89E-03	6.68E-03	6.42E-03	8.54E-03	37.14
<b>CM3</b>	2.21E-04	3.01E-04	2.64E-04	5.27E-04	30.10	5.88E-03	6.83E-03	6.42E-03	8.54E-03	44.74
<b>CM4</b>	2.10E-04	2.37E-04	2.64E-04	5.27E-04	<b>10.33</b>	5.93E-03	6.31E-03	6.42E-03	8.54E-03	<b>18.09</b>

Additionally, it is observed that due to the emissive properties of the materials and the atmospheric absorption characteristics in the MWIR and LWIR spectral ranges, the thermal transmission through the material samples exhibits significant differences. In general, the thermal transmission of the materials in the MWIR range is considerably lower than in the LWIR range.

To validate the laboratory evaluation results obtained using the proposed method, the authors conducted field experiments and independently assessed the thermal camouflage effectiveness of the camouflage material samples, separate from the laboratory-measured thermal transmission values. For the field evaluation, the authors employed a quantitative assessment method based on image similarity using the DEA model [26]. Images of the camouflaged targets and their backgrounds were captured using a Moskito-TI thermal imaging camera operating in the LWIR range. Therefore, this field experiment was only able to verify the camouflage effectiveness of the materials within the LWIR spectral range. Based on the DEA evaluation model detailed in [26], the ranking of the thermal camouflage effectiveness of the samples is as follows: CM4 > CM1 > CM2 > CM3. Both the laboratory and field evaluation results indicate that the CM4 thermal camouflage material demonstrates the highest effectiveness, followed by CM1. However, the ranking of CM2 and CM3 shows some inconsistencies, which may be attributed to the fact that the field evaluation criteria only consider characteristics derived from thermal imaging data in the LWIR spectral range, without accounting for spectral radiance data.

#### 4. CONCLUSIONS

The paper introduces a method for measuring the thermal transmission coefficient of camouflage materials in the laboratory using the SR-5000N spectroradiometer, available at the Physical-Technical Institute. Developed from recent, rare publications and referenced in Sweden's MLCN technical specifications, this advanced and reliable device ensures a scientifically robust method. Independent field tests of camouflage effectiveness showed consistent results with laboratory measurements, demonstrating the method's potential for standardization and application as a benchmark in domestic camouflage research.

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### TÓM TẮT

#### **Phương pháp xác định tỉ lệ truyền bức xạ nhiệt qua tấm vật liệu ngụy trang ảnh nhiệt sử dụng máy đo phổ bức xạ từ xa SR-5000N**

Nghiên cứu ngụy trang trong nước gần đây đòi hỏi các phương pháp, kỹ thuật đánh giá tiêu chuẩn hóa để kiểm tra vật liệu ngụy trang (như vải, lưới ngụy trang) một cách khoa học và đáng tin cậy. Đây là thách thức lớn do tính bảo mật cao của lĩnh vực và hạn chế về thiết bị thí nghiệm. Dựa trên một số tiêu chuẩn đã được các quốc gia tiên tiến công bố, bài báo đã đề xuất phương pháp xác định tỉ lệ truyền bức xạ nhiệt qua tấm vật liệu ngụy trang trong phòng thí nghiệm bằng thiết bị SR-5000N được trang bị. Phương pháp đề xuất có nhiều ưu điểm là thực hiện nhanh chóng, chính xác, tin cậy với dải phổ rộng bao gồm hai vùng phổ chính của ngụy trang ảnh nhiệt là MWIR và LWIR. Kết quả đánh giá độc lập tại thực địa đã chứng minh tính phù hợp của phương pháp đề xuất, giúp tiết kiệm thời gian và nguồn lực trong hoạt động đánh giá hiệu quả ngụy trang ảnh nhiệt.

**Từ khóa:** Ngụy trang ảnh nhiệt; Dấu hiệu nhiệt; Hệ số phát xạ; Hệ số truyền nhiệt; Thiết bị đo phổ bức xạ SR-5000N.