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A Proposition to Correct Infrared Emissivity Measurements for Curved Surface Targets Based on the Irradiation Reflection Method

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Abstract: In this paper, a measurement correction method is proposed to correct the error of the irradiation reflection method when measuring the emissivity of curved surface targets. First, by introducing an angle parameter related to the target surface shape, the formulas of emissivity measurements for curved surface targets under various types of radiation sources were obtained. Then, the variation law of these emissivity measurement formulas was analyzed, the concept of the measurement correction factor was proposed, and then a unified correction measurement formula was obtained. Finally, a scene of measuring the emissivity of a curved surface target based on the irradiation reflection method was simulated. Different target emissivities and different distances between the radiation source and target were set, and the errors between the measured and corrected emissivities were compared. The results revealed that the proposed method could effectively correct the error caused by the curvature of the target surface when measuring its emissivity by the irradiation reflection method. This is of great significance to expanding the application scope of the irradiation reflection method and improving the measurement accuracy.



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1. Introduction

Emissivity represents the ability of an object to emit radiation, which is a key parameter in the field of infrared physics and technology. Especially in the application of noncontact radiation thermometry, according to Stephen–Boltzmann's law, the measurement results of emissivity directly affect the measurement accuracy of temperature. In addition, emissivity measurement also plays an important role in the damage detection of infrared low emissivity coatings [1–3].

Emissivity measurement methods can be divided into direct and indirect ones [4–7]; their theories and applications have been widely studied by scholars and technicians in the field [8–10]. The irradiation reflection method proposed by Li et al. [5] is an indirect infrared emissivity measurement method based on a thermal imager. By actively irradiating the target twice, the reflectance of the target surface can be obtained, and then the emissivity can be obtained according to its relationship with reflectance. The irradiation reflection method is in situ, rapid, and convenient, and can realize noncontact emissivity measurement, which has a good application prospect for objects that are difficult to access or easy to damage, e.g., coatings [5,10].

However, two key problems exist in practical applications of the irradiation reflection method. One is the problem of measuring distance. When using a point source or an extended source as the radiation source, the position close to the point source or extended source center receives strong radiation, while the position far away receives weak radiation in a short-range test, which is inconsistent with the assumption of uniform radiation, resulting in measurement errors [1,5,11]. The second is the problem of target shape since planar targets are the objective of the theory. For curved surfaces, even if the incident

radiation is parallel and uniform, the curvature of the target surface itself will cause the irradiance received to vary at different positions, which seriously deviates from the theoretical assumption and causes errors [5,12]. Especially for the infrared emissivity measurement of military aircraft skin and aeroengine nozzle coating, almost all surfaces have curvature, and the measurement error generated needs to be given careful attention.

In the study of Li et al. [5], the measurement target was a planar coated plate, and the distance between the radiation source and the target was increased to better simulate uniform irradiation, thus achieving a good measurement effect. However, no suitable measurement scheme was provided for in short-range scenarios and curved surface targets that are possible in practical applications.

Later, to correct the error caused by the uneven distribution of target surface irradiance in the irradiation reflection method, Zhang et al. [1] conducted research on the calculation of infrared extended-source surface irradiances and proposed a progressive irradiance calculation method. Through this method, the irradiance distribution on the target surface could be accurately calculated under short-range test conditions, so as to complete the correction for the emissivity measurement error. However, the research still aimed at planar targets without discussing emissivity measurement correction for curved targets.

In addition, Peeters et al. [12] calculated the directional emissivity of the surface by using the finite element (FE) model, and then modified the temperature measurement of the surface; Zhou et al. [13] studied the influence of observation distance and viewing angle on infrared radiation temperature measurement, accumulated a large amount of data through measurement experiments at different distances and viewing angles, and proposed a correction method based on data fitting; Fu et al. [14] obtained the temperature correction coefficient by analyzing the relationship between the directional emissivity and the measured temperature, and realized the temperature measurement correction for nonplanar targets based on a point cloud 3D mapping model.

The analysis above reveals that the emissivity measurement of curved targets is not well solved in existing studies on the irradiation reflection method. In the existing research on infrared measurement and correction for curved surfaces, more focus is on the correction for temperature measurement, while the research on emissivity measurement and correction is rare. Therefore, research on emissivity measurement and correction for curved surface targets based on the irradiation reflection method is carried out in this paper. Firstly, by analyzing the principle of the irradiation reflection method, the mechanism of how the curved object affects the emissivity measurement by the irradiation reflection method is explained. Then, the physical illumination equation is introduced into the original theoretical formula, and the measurement formula is deduced again, which contains the shape information of the target surface and is applicable to curved surface targets. Next, according to the new measurement formula, the corrected emissivity measurement method for curved surface targets is proposed, the variation law of the measurement formulas when different types of radiation sources are applied is analyzed, the measurement correction factor k and the corrected measurement formula are proposed, and the calculation formula for k under typical scenarios is given. Finally, an example scene of the irradiation reflection method adopted for a curved surface target is simulated. Different target emissivities and different distances between the radiation source and target are set, and the errors between the measured and corrected emissivities are compared. The effectiveness of the proposed correction method is verified.

2. Theories and Methods

2.1. Principle of Measuring Infrared Emissivity by the Irradiation Reflection Method

The irradiation reflection method is an indirect method to measure the object surface emissivity, which uses an infrared radiation source to emit to the object surface. The radiation reflected from the object surface contains the reflectance information of the surface. For opaque objects, according to the law of energy conservation and Kirchhoff's law, the reflectance of the surface has a definite relationship with its emissivity. Therefore,

by applying two active irradiations with different energies, two sets of relations of the reflected energy from the object are obtained. The emissivity of the target surface can then be obtained by eliminating the unknown parameters by subtraction. The specific principle is as follows.

When the infrared radiation source is not used, suppose the target has a Lambertian diffuse reflection surface with a constant temperature, so the radiance L of the coating surface received by the infrared detector in a certain fixed wavelength range or at a certain wavelength can be expressed as [5,11,15]:

$$L = \tau(L_s + \rho \cdot L_e) + L_a \quad (1)$$

where τ is the average atmospheric transmittance; L_s is the radiance emitted by the target itself; ρ is the target reflectivity; L_e is the equivalent ambient radiance; and L_a is the atmospheric path radiance. Unless otherwise stated, all parameters in this paper are those at the corresponding wavelength or band of the detector.

First, the radiation source is used to irradiate the target surface for the first time. As shown in Figure 1, the radiance produced by the irradiation on the target surface is L_{r1} . Because the irradiation time is short, it is assumed that the temperature of the target surface has not changed. According to Equation (1), the radiance L_1 of the target surface received by the infrared detector is expressed by

$$L_1 = \tau[L_s + \rho \cdot (L_e + L_{r1})] + L_a \quad (2)$$

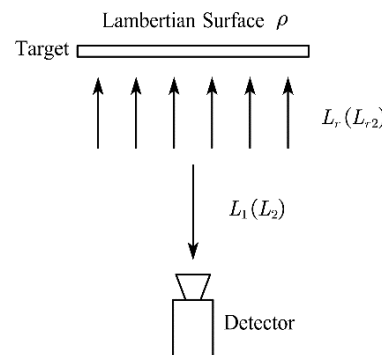


Figure 1. Schematic diagram of the measurement principle of the irradiation reflection method.

The second irradiation is applied to the target surface within a short period under the same environment. As shown in Figure 1, the radiance generated by the irradiation on the target surface is L_{r2} . At this time, according to Equation (1), the radiance L_2 of the target surface received by the infrared detector is expressed by

$$L_2 = \tau[L_s + \rho \cdot (L_e + L_{r2})] + L_a \quad (3)$$

By subtracting Equations (2) and (3), parameters that are difficult to measure, such as L_s , L_e , and L_a , can be eliminated. Through transformation and sorting, the following formula can be obtained:

$$\rho = \frac{L_2 - L_1}{\tau \cdot (L_{r2} - L_{r1})} \quad (4)$$

According to the law of energy conservation and Kirchhoff's law, when the object temperature is kept constant, the energy it absorbs is equal to the energy it emits, i.e., $\varepsilon = \alpha$. For opaque objects, $\varepsilon = 1 - \rho$, substituting this into Equation (4) obtains:

$$\varepsilon = 1 - \rho = 1 - \frac{L_2 - L_1}{\tau \cdot (L_{r2} - L_{r1})} \quad (5)$$

Equation (5) is the measurement formula of target surface emissivity, but it is difficult to directly obtain the atmospheric transmittance τ and the radiances L_{r1} and L_{r2} generated by the two active irradiations, so the irradiation reflection method completes the measurement by introducing a reference body with known reflectance (or emissivity).

The reference body is placed in the same environment as the target and close to it. As shown in Figure 2, it is deemed that the surface of the reference body is subject to the same irradiation as the target surface. According to Equation (4), the relationship between the radiances of the reference body surface can be obtained as follows:

$$L_{r2} - L_{r1} = \frac{L_{c2} - L_{c1}}{\tau \cdot \rho_c} \quad (6)$$

where L_{c1} and L_{c2} are the radiances of the surface of the reference body received by the infrared detector under the two active irradiations, respectively; and ρ_c is the reflectance of the reference body. The emissivity measurement formula based on the irradiation reflection method can be obtained by substituting Equation (6) into Equation (5):

$$\varepsilon = 1 - \rho_c \cdot \frac{L_2 - L_1}{L_{c2} - L_{c1}} \quad (7)$$

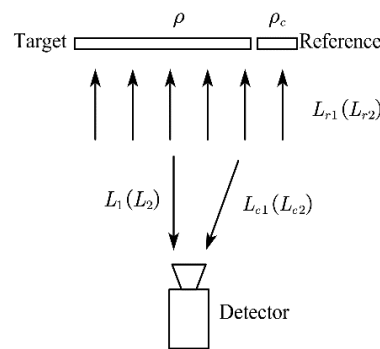


Figure 2. Schematic diagram of introducing a reference body in the measurement.

According to the principle of the irradiation reflection method, this approach can effectively achieve noncontact measurements, which is barely affected by environmental factors and has a simple operation procedure. However, Equation (7) only holds if the same radiation is received at each measured position on the target surface and the reference body surface. For curved surface objects, even if the radiation L_r is uniform, the irradiance received by each position varies due to their different normal directions on the surface. If the target surface is still the Lambertian surface, the reflected radiances L_{rp1} , L_{rp2} , and L_{rp3} are also different. As shown in Figure 3, direct use of the irradiation reflection method produces a large measurement error that needs to be corrected.

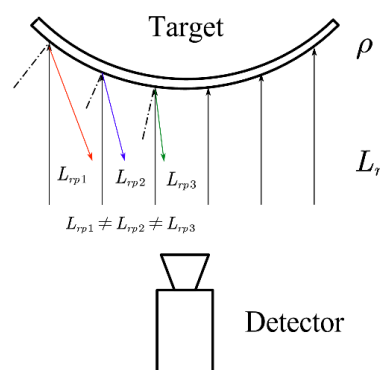


Figure 3. Radiances reflected by a curved surface are not equal.

2.2. Introducing an Angle Parameter into the Formula of the Irradiation Reflection Method

Compared with a planar target, the curved target additionally involves the relationship between radiance and incident angle. Therefore, to analyze the effect of the curved surface on the measured emissivity, an angle parameter needs to be introduced into the original theoretical formula.

For a planar object in an ideal environment, as shown in Figure 4, according to the physical illumination equation [16], the radiance L_o received by the detector is expressed by

$$L_o = L_s(\omega_o) + \int_{\Omega} f(\omega_i, \omega_o) L_i(\omega_i) \cos \omega_i d\Omega_i \quad (8)$$

where ω_i signifies the direction of incidence; ω_o is the direction of emission to the detector; $L_s(\omega_o)$ is the radiance emitted by the target itself in the direction of ω_o ; $L_i(\omega_i)$ is the external radiance incident on the target surface in the direction of ω_i ; $f(\omega_i, \omega_o)$ is the bidirectional reflectance distribution function (BRDF) [17,18] of the target surface; Ω_i is the space angle cell of incidence; Ω represents the whole hemisphere space; and the second term on the right side of Equation (8) denotes the radiance reflected by the object surface in the direction of ω_o .

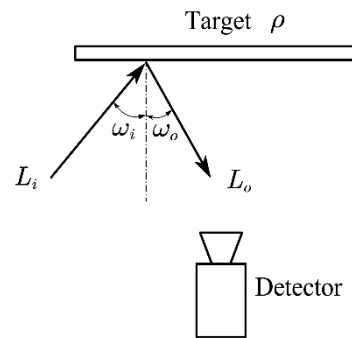


Figure 4. Radiation received by the detector from a planar object.

In reality, the effects of environmental radiation, atmospheric transmittance, and atmospheric radiation need to be considered. Assuming that the environmental radiation is isotropic, as shown in Figure 5, the radiance L_o received by the detector from a certain position on the object surface is

$$L_o = \tau \left(L_s(\omega_o) + \int_{\Omega} f(\omega_i, \omega_o) L_e(\omega_i) \cos \omega_i d\Omega_i \right) + L_a \quad (9)$$

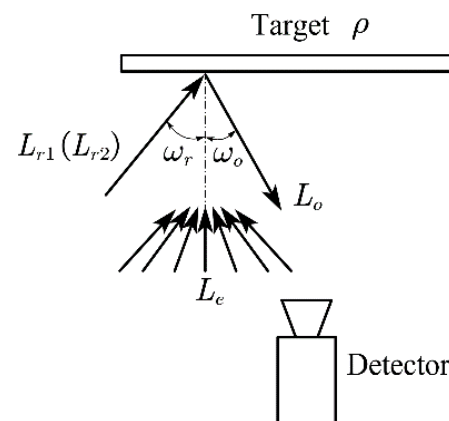


Figure 5. Radiation received by the detector from a planar object.

Assuming that the object is irradiated by L_{r1} uniformly in the direction of ω_r , as shown in Figure 5, the expression becomes

$$L_{d1} = L_o + \tau f(\omega_r, \omega_o) L_{r1} \cos \omega_r d\Omega_r \quad (10)$$

In the same scenario, assuming that the object is irradiated by L_{r2} uniformly in the direction of ω_r , the expression becomes

$$L_{d2} = L_o + \tau f(\omega_r, \omega_o) L_{r2} \cos \omega_r d\Omega_r \quad (11)$$

Equation (11) minus Equation (10) yields

$$L_{d2} - L_{d1} = \tau f(\omega_r, \omega_o) (L_{r2} - L_{r1}) \cos \omega_r d\Omega_r \quad (12)$$

Similarly, in the same environment, a reference body with a reflectance of ρ_c is also irradiated by L_{r1} and L_{r2} , so

$$L_{c2} - L_{c1} = \tau f_c(\omega_r, \omega_o) (L_{r2} - L_{r1}) \cos \omega_r d\Omega_r \quad (13)$$

For a Lambertian diffuse reflector, the BRDF is fixed [1,19], which is

$$\begin{aligned} f(\omega_r, \omega_o) &= \frac{\rho}{\pi} \\ f_c(\omega_r, \omega_o) &= \frac{\rho_c}{\pi} \end{aligned} \quad (14)$$

Dividing the two sides of Equation (12) by Equation (13) and considering Equation (14), we obtain

$$\frac{L_{d2} - L_{d1}}{L_{c2} - L_{c1}} = \frac{\tau \frac{\rho}{\pi} (L_{r2} - L_{r1}) \cos \omega_r d\Omega_r}{\tau \frac{\rho_c}{\pi} (L_{r2} - L_{r1}) \cos \omega_r d\Omega_r} = \frac{\rho}{\rho_c} \quad (15)$$

Since $\varepsilon = 1 - \rho$, Equation (15) can also be written as

$$\varepsilon = 1 - \rho_c \cdot \frac{L_{d2} - L_{d1}}{L_{c2} - L_{c1}} \quad (16)$$

Equation (16) is the emissivity measurement formula for a planar target after introducing the angle parameter, which is equivalent to the emissivity measurement Equation (7) of the original irradiation reflection method. However, the angle parameter, i.e., the shape information of the target surface, is included in the derivation, based on which the formula for calculating the emissivity of curved surface targets can be derived.

2.3. Derivation of Emissivity Measuring Formulas for Surface Targets under Various Irradiation Modes

2.3.1. Applying a Uniform, Parallel Irradiation

Before applying the irradiation, the radiance L_d received by the detector from a certain position on the object surface is

$$L_d = \tau \left(L_s(\omega_{o1}) + \int_{\Omega} f(\omega_i, \omega_{o1}) L_e(\omega_i) \cos \omega_i d\Omega_i \right) + L_a \quad (17)$$

After applying a uniform parallel radiance L_{ur1} , as shown in Figure 6, the corresponding radiance received by the detector becomes

$$L_{ud1} = L_d + \tau f(\omega_{r1}, \omega_{o1}) L_{ur1} \cos \omega_{r1} d\Omega_r \quad (18)$$

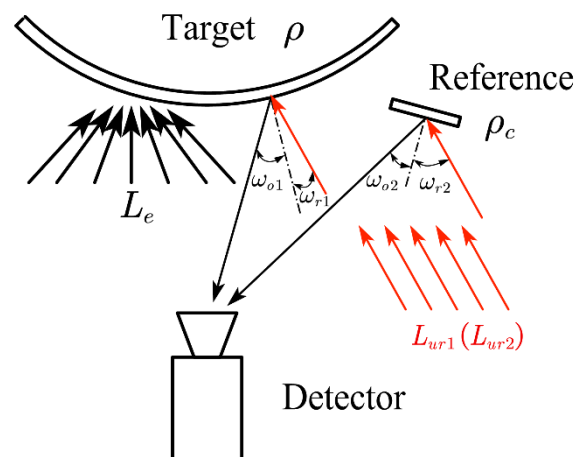


Figure 6. Schematic diagram of the measurement scene under uniform irradiation.

Changing the radiance to L_{ur2} , the radiance received by the detector from the same object point becomes

$$L_{ud2} = L_d + \tau f(\omega_{r1}, \omega_{o1}) L_{ur2} \cos \omega_{r1} d\Omega_r \quad (19)$$

Equation (19) minus Equation (18) yields

$$L_{ud2} - L_{ud1} = \tau f(\omega_{r1}, \omega_{o1}) (L_{ur2} - L_{ur1}) \cos \omega_{r1} d\Omega_r \quad (20)$$

A similar equation can be obtained for the reference body:

$$L_{uc2} - L_{uc1} = \tau f_c(\omega_{r2}, \omega_{o2}) (L_{ur2} - L_{ur1}) \cos \omega_{r2} d\Omega_r \quad (21)$$

In this case, the emissivity obtained by directly substituting the measured value into Equation (16) is not a true emissivity. Let

$$\hat{\varepsilon} = 1 - \rho_c \cdot \frac{L_{ud2} - L_{ud1}}{L_{uc2} - L_{uc1}} \quad (22)$$

Therefore,

$$\hat{\varepsilon} = 1 - \rho_c \cdot \frac{\tau \frac{\rho}{\pi} (L_{ur2} - L_{ur1}) \cos \omega_{r1} d\Omega_r}{\tau \frac{\rho_c}{\pi} (L_{ur2} - L_{ur1}) \cos \omega_{r2} d\Omega_r} = 1 - \rho \frac{\cos \omega_{r1}}{\cos \omega_{r2}} \quad (23)$$

$\varepsilon = 1 - \rho$ holds, so the formula for measuring the emissivity under parallel, uniform incident irradiation should be

$$\varepsilon = 1 - \frac{\cos \omega_{r2}}{\cos \omega_{r1}} (1 - \hat{\varepsilon}) \quad (24)$$

2.3.2. Applying a Point Source Irradiation

When a point source with a radiant intensity of I_{pr1} as shown in Figure 7 is applied, for a target object point at a distance of r_1 from the source, the radiance received by the detector from that point is

$$L_{pd1} = L_d + \tau f(\omega_{r1}, \omega_{o1}) \frac{I_{pr1} \cos \omega_{r1}}{r_1^2} d\Omega_r \quad (25)$$

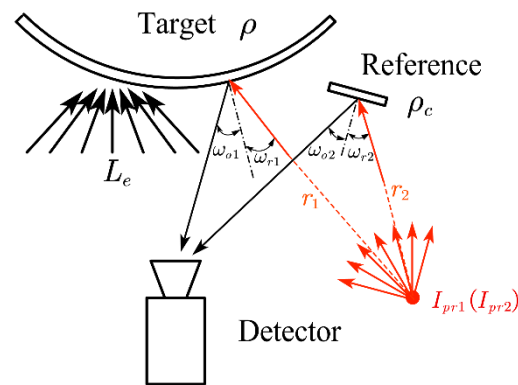


Figure 7. Schematic diagram of a measurement scene irradiated by a point source.

Changing the radiant intensity to I_{pr2} , the radiance received by the detector from the same point is

$$L_{pd2} = L_d + \tau f(\omega_{r1}, \omega_{o1}) \frac{I_{pr2} \cos \omega_{r1}}{r_1^2} d\Omega_r \quad (26)$$

Equation (26) minus Equation (25) yields

$$L_{pd2} - L_{pd1} = \tau f(\omega_{r1}, \omega_{o1}) (I_{pr2} - I_{pr1}) \frac{\cos \omega_{r1}}{r_1^2} d\Omega_r \quad (27)$$

Similarly, a similar equation can be obtained for the reference body:

$$L_{pc2} - L_{pc1} = \tau f_c(\omega_{r2}, \omega_{o2}) (I_{pr2} - I_{pr1}) \frac{\cos \omega_{r2}}{r_2^2} d\Omega_r \quad (28)$$

Similarly, let

$$\hat{\varepsilon} = 1 - \rho_c \cdot \frac{L_{pd2} - L_{pd1}}{L_{pc2} - L_{pc1}} \quad (29)$$

Then,

$$\hat{\varepsilon} = 1 - \rho_c \cdot \frac{\tau \frac{\rho}{\pi} (I_{pr2} - I_{pr1}) \frac{\cos \omega_{r1}}{r_1^2} d\Omega_r}{\tau \frac{\rho_c}{\pi} (I_{pr2} - I_{pr1}) \frac{\cos \omega_{r2}}{r_2^2} d\Omega_r} = 1 - \rho \frac{r_2^2 \cos \omega_{r1}}{r_1^2 \cos \omega_{r2}} \quad (30)$$

Again, since $\varepsilon = 1 - \rho$, the formula for measuring the emissivity when a point irradiation source is applied should be

$$\varepsilon = 1 - \frac{r_1^2 \cos \omega_{r2}}{r_2^2 \cos \omega_{r1}} (1 - \hat{\varepsilon}) \quad (31)$$

2.3.3. Applying a Small-Surface Source Irradiation

Apply a small-surface source with a radiance of L_{xr1} and an area of ΔA_x , as shown in Figure 8, for a certain point on the target object at a distance of r_1 from the source, the radiance received by the detector from that point is

$$L_{xd1} = L_d + \tau f(\omega_{r1}, \omega_{o1}) \frac{L_{xr1} \Delta A_x \cos \omega_{x1} \cos \omega_{r1}}{r_1^2} d\Omega_r \quad (32)$$

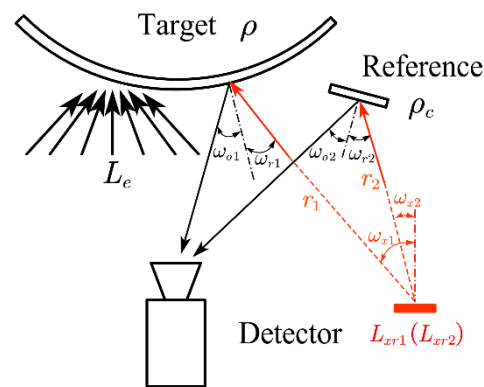


Figure 8. Schematic diagram of a measurement scene irradiated by a small-surface source.

Change the radiance of the small-surface source to L_{xr2} , the radiance received by the detector from that same point becomes

$$L_{xd2} = L_d + \tau f(\omega_{r1}, \omega_{o1}) \frac{L_{xr2} \Delta A_x \cos \omega_{x1} \cos \omega_{r1}}{r_1^2} d\Omega_r \quad (33)$$

Equation (33) minus Equation (32) yields

$$L_{xd2} - L_{xd1} = \tau f(\omega_{r1}, \omega_{o1}) (L_{xr2} - L_{xr1}) \frac{\Delta A_x \cos \omega_{x1} \cos \omega_{r1}}{r_1^2} d\Omega_r \quad (34)$$

Similarly, a similar equation can be obtained for the reference body:

$$L_{xc2} - L_{xc1} = \tau f_c(\omega_{r2}, \omega_{o2}) (L_{xr2} - L_{xr1}) \frac{\Delta A_x \cos \omega_{x2} \cos \omega_{r2}}{r_2^2} d\Omega_r \quad (35)$$

Similarly, let

$$\hat{\varepsilon} = 1 - \rho_c \cdot \frac{L_{pd2} - L_{pd1}}{L_{pc2} - L_{pc1}} \quad (36)$$

Then,

$$\hat{\varepsilon} = 1 - \rho_c \cdot \frac{\tau \frac{\rho}{\pi} (L_{xr2} - L_{xr1}) \frac{\Delta A_x \cos \omega_{x1} \cos \omega_{r1}}{r_1^2} d\Omega_r}{\tau \frac{\rho_c}{\pi} (L_{xr2} - L_{xr1}) \frac{\Delta A_x \cos \omega_{x2} \cos \omega_{r2}}{r_2^2} d\Omega_r} = 1 - \rho \frac{r_2^2 \cos \omega_{x1} \cos \omega_{r1}}{r_1^2 \cos \omega_{x2} \cos \omega_{r2}} \quad (37)$$

Therefore, the formula for measuring the emissivity when a small-surface source is applied should be

$$\varepsilon = 1 - \frac{r_1^2 \cos \omega_{x2} \cos \omega_{r2}}{r_2^2 \cos \omega_{x1} \cos \omega_{r1}} (1 - \hat{\varepsilon}) \quad (38)$$

2.4. Introducing a Correction Factor for Emissivity Measurements of Curved Surface Targets

According to the result of Section 2.3, for curved diffuse reflection surfaces, the emissivity $\hat{\varepsilon}$ measured by the original irradiation reflection method is not the true target emissivity ε ; the two have a definite relationship that can be expressed as

$$\varepsilon = 1 - k(1 - \hat{\varepsilon}) \quad (39)$$

In addition, letting

$$\hat{\rho} = \rho_c \cdot \frac{L_2 - L_1}{L_{C2} - L_{C1}} \quad (40)$$

then $\hat{\varepsilon} = 1 - \hat{\rho}$ holds, and the true emissivity of the target can also be expressed as

$$\varepsilon = 1 - k\hat{\rho} \quad (41)$$

Equations (39) and (41) are the correction formulas for emissivity measurements of the irradiation reflection method. Here, k is called the measurement correction factor; $\hat{\varepsilon}$ and $\hat{\rho}$ are both direct results of the irradiation reflection method. The correction factor k is related to the shape and position of the target, reference body, and radiation source, as shown in Table 1.

Table 1. Formulas of correction factor k .

Scenario	k
Planar target, parallel irradiation	1
Curved surface target, parallel irradiation	$\frac{\cos \omega_{r2}}{\cos \omega_{r1}}$
Curved surface target, point source irradiation	$\frac{r_1^2 \cos \omega_{r2}}{r_2^2 \cos \omega_{r1}}$
Curved surface target, small-surface source irradiation	$\frac{r_1^2 \cos \omega_{r2} \cos \omega_{r2}}{r_2^2 \cos \omega_{r1} \cos \omega_{r1}}$

The reason for considering small-surface and point source irradiations is that extended sources (e.g., area blackbody) are commonly used in the irradiation reflection method. For them, when $R/l \leq 1/10$, i.e., $l \geq 10R$, the following holds:

$$\frac{E_0 - E}{E} \leq \frac{1}{100} \quad (42)$$

In other words, if the extended source has a linearity equal to or less than 1/10 of the distance between the it and the illuminated surface, the extended source can be regarded as a small-surface source (or point source), and the relative error between the obtained radiance and the accurately calculated result is equal to or less than 1/100 [13]. According to the proposed correction method, as long as the included angle between the normal direction of the target surface and the radiation direction is less than 90°, the correction factor of the corresponding position can be calculated. When the included angle is greater than 90°, it usually means that the target position is blocked by other parts of the surface. In the actual measurement based on the radiation reflection method, within the field of view of the thermal imager, the angle between the normal direction of the target surface and the radiation direction should be as small as possible, so as to reduce the measurement error.

3. Calculation Results

3.1. Construction of Simulation Measurement Scene

A simulation scene for measuring the emissivity of a curved surface based on the irradiation reflection method was constructed, and the progressive irradiation calculation method (PICM) [1] was used for infrared calculation. The curved surface was one-quarter of a cylindrical surface with a radius of 150 mm and a height of 200 mm, as shown in Figure 9. The emissivity of the surface was ε , which is equal to $1 - \rho$. A standard diffuse plate with a reflectance $\rho_c = 0.5$ was selected as the reference body. The reference surface was a square with a side length of 30 mm, the test distance was l , and the distance d between the centers of the reference body and the target was 135 mm. A point source was applied to the reference body and the target, as shown in Figure 9. Since the objects in the scene are diffuse reflectors, the measurement results are not affected by the detector position. Based on the radiance received by the detector, the emissivity distribution on the target surface was obtained by the irradiation reflection method.

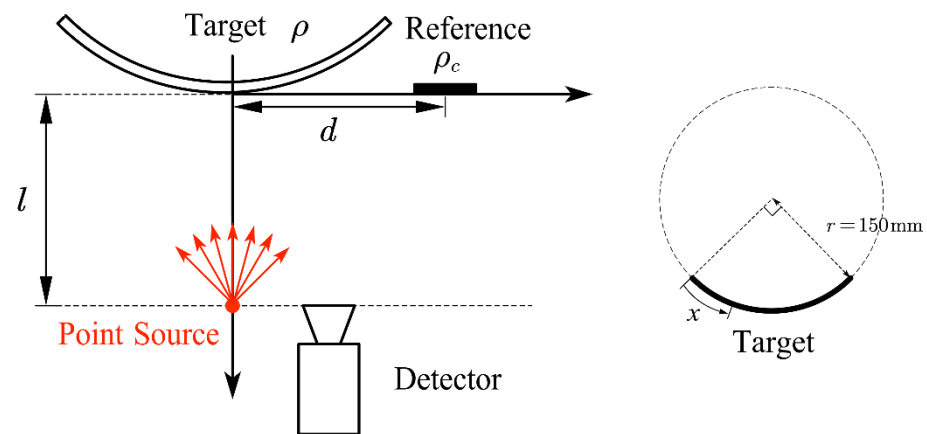


Figure 9. Schematic diagram of the measurement scene and curved surface target shape.

For convenient comparison of results, the intersection line between the horizontal plane where the detector was located and the target surface was selected as the research subject. The x in Figure 9 represents the distance relative to the leftmost end along the intersecting line.

3.2. Testing of Targets with Different Emissivity

First, set l to 1500 mm, the irradiation reflection method is directly used to measure targets with different emissivity, and the measurement results are shown in Figure 10.

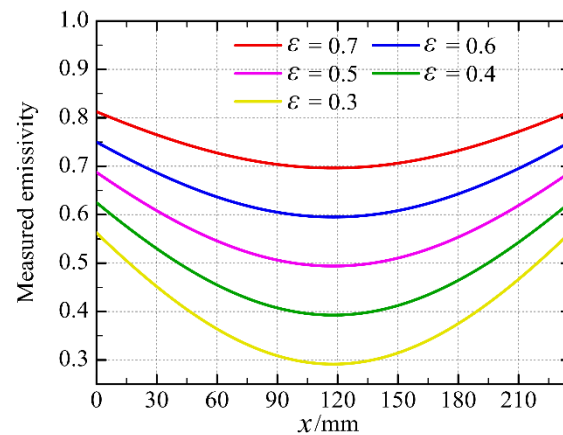


Figure 10. Emissivity measurements obtained directly by the irradiation reflection method.

The average value, maximum relative error, and average relative error of the emissivity measurements by the irradiation reflection method are shown in Table 2.

Table 2. Average value and maximum and average relative errors of emissivity measurements.

True Emissivity	Measured Average	Maximum Relative Error	Average Relative Error
0.3	0.3890	87.56%	29.68%
0.4	0.4763	56.29%	19.08%
0.5	0.5636	37.53%	12.72%
0.6	0.6509	25.02%	8.48%
0.7	0.7382	16.08%	5.45%

According to the measurement correction factor theory proposed in Section 2.4, the correction factor k in this scenario is expressed by

$$k = \frac{r_1^2 \cos \omega_{r2}}{r_2^2 \cos \omega_{r1}} \quad (43)$$

According to the measurement method in reference [5], when calculating the parameters related to the reference, the average value of the whole reference surface can effectively reduce the error in the actual measurement. The distribution of the correction factor along the intersection line calculated from Equation (43) is shown in Figure 11. In the calculation, r_2^2 and $\cos \omega_{r2}$ related to the reference are the average values calculated on the whole reference plane.

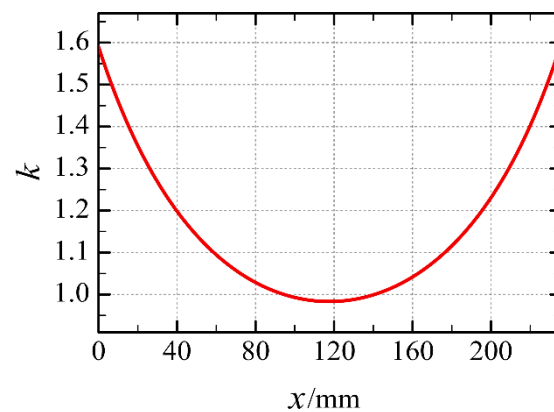


Figure 11. Distribution of the correction factor on the research subject.

The direct measurement results of the irradiation reflection method were corrected by using Equation (39) and the corresponding correction factor, and the corrected results are shown in Figure 12. The lines in the figure represent the corrected measurement results for the corresponding emissivity.

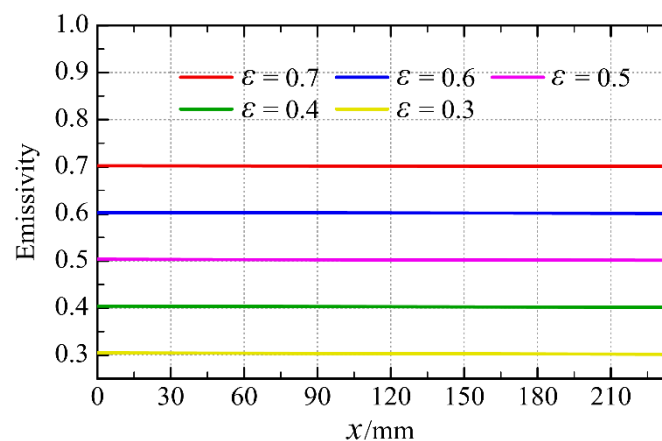


Figure 12. Corrected emissivity calculation results.

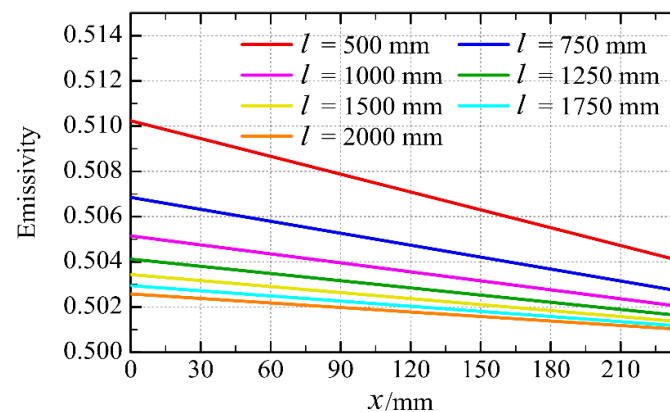
The average value, maximum relative error, and average relative error of the corrected emissivity measurement results are shown in Table 3.

Table 3. Average value and maximum and average relative errors of corrected emissivity.

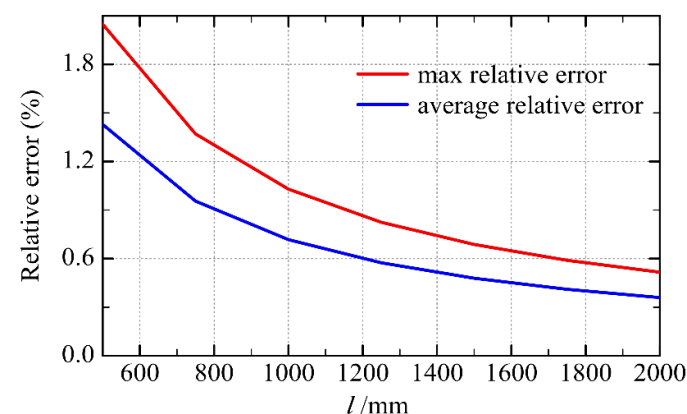
True Emissivity	Corrected Average	Maximum Relative Error	Average Relative Error
0.3	0.3034	1.60%	1.12%
0.4	0.4029	1.09%	0.72%
0.5	0.5024	0.69%	0.48%
0.6	0.6019	0.46%	0.32%
0.7	0.7014	0.29%	0.21%

3.3. Testing of Targets with Different Distances l

Set the emissivity of the target surface to 0.5 and the distance l to 500, 750, 1000, 1250, 1500, 1750, 2000 mm. Carry out emissivity tests based on the irradiation reflection method at these distances, and use the correction method proposed in this paper to correct the results, which are shown in Figure 13.

**Figure 13.** Corrected emissivity calculation results at different distances l .

The changes in the average relative error and the maximum relative error of the corrected emissivity with l are shown in Figure 14.

**Figure 14.** The change in average relative error and maximum relative error of corrected emissivity with l .

4. Discussion

As described in Equation (14), the BRDF of a Lambertian diffuse reflector is a fixed value. In other words, when the incident radiance is fixed, the radiances reflected in all directions are the same, regardless of the incidence direction. For planar objects, when the incident radiation is uniform and parallel, its intensity and direction are the same at any position on the plane, so the generated radiances produced at the corresponding position

are also equal. The original irradiation reflection method requires that both the target and the reference body are exposed to the same active irradiation. Since both of them are Lambertian radiators, the actual requirement is that the incident radiation produces the same irradiance on both the target and reference body surfaces, which is obvious from the derivation of the measurement formula. In reference [5], an area blackbody was used as the radiation source, so the radiation emitted by the blackbody as the extended source was not uniform. Therefore, the distance between the radiation source and the target was increased to better simulate the uniform radiation scene, thereby meeting the theoretical requirements for measurement.

However, for a curved surface object, because the normal direction of the surface changes, even if the incident radiation is uniform and parallel, the angle between the radiation direction and the normal direction of the surface varies, which results in different radiances on the surface. Therefore, the conditions of the irradiation reflection method cannot be directly met, causing errors in the measurement results, as shown by the formula derivation process in Section 2.3.1.

In Section 2.4, a measurement correction factor k is proposed after analyzing the variation in the measurement formulas under the three irradiation conditions described in Section 2.3. The correction factor k describes the difference between the radiances produced by the incident radiation at the corresponding position of the target and the reference body. According to the expression of k , its value is only related to the target surface shape, radiation source type, and spatial position relationship between them, but not related to the specific measurement parameters, so it can be determined before the measurement. For example, in the calculation of Section 3, only one correction factor distribution needs to be calculated for targets with the same shape but different emissivities, as shown in Figure 11. In practical measurements, after obtaining the target surface shape and the positional relationship between the target and the radiation source by spatial localization and modeling, the correction factor distribution on the whole target surface can be calculated based on the type of radiation source. The true emissivity ε can then be obtained by using the value of $\hat{\varepsilon}$ or $\hat{\rho}$ from the irradiation reflection method and the measurement correction according to Equation (39) or (41). In addition, as shown in Section 2.3, the correction method can be easily applied to different types of radiation sources, which further expands the application scope of the irradiation reflection method.

In Section 3, a curved surface emissivity measurement scene based on the irradiation reflection method is constructed, and the direct measurement results obtained by this method are shown in Figure 10. As can be seen in the figure, the maximum error in emissivity measurements occurs at the boundary of the cylindrical target. This is because in this scenario, the angle between the normal direction at the target boundary and the radiation direction of the point source is the largest, that is, when the same radiance is received, the radiance produced at the target boundary is lower, so the reflected radiance is lower. For planar objects, under the same radiation condition, the smaller the reflected radiance, the smaller the reflectivity of the target, and the higher the corresponding emissivity. The direct use of the irradiation reflection method assumes that the target is treated as a plane, so the emissivity measurements at the cylindrical target boundary are high and contain large errors. The convex curves in Figure 10 validate this explanation. In addition, the correction factor k describes the difference between the radiances produced by the incident radiation at the corresponding target location and the reference body surface. The same conclusion can be obtained from the distribution of correction factor k on the target surface shown in Figure 11.

In Section 3.2, set the distance $l = 1500$ mm. As shown by the measurement error of the irradiation reflection method given in Table 2, the curved surface with a lower emissivity was affected more. For a target with 0.3 emissivity, the maximum relative error of measurement was 87.56%, and the average relative error was 29.68%. For a target with an emissivity of 0.7, however, the maximum relative error was 16.08%, and the average relative error was only 5.45%. This was because the object with a low emissivity had

a higher reflectivity, and the change in reflected energy was more obvious. What the irradiation reflection method actually captured was the change in reflected energy of the object. Furthermore, the target itself had a low true emissivity, which increased the relative error as a whole. Objects with a high emissivity experienced an opposite effect, so the overall relative error was small.

The measurement results were corrected using the correction factor distribution shown in Figure 11, and the correction effect is shown in Figure 12. Evidently, the measurement result after modification by the correction factor almost coincided with the true value. For the target with the emissivity of 0.3, the maximum relative error is reduced to 1.60%, and the average relative error is reduced to 1.12%; for targets with emissivity of 0.7, the maximum relative error is 0.29%, and the average relative error is only 0.21%. The results proved that the proposed method could effectively correct measurements of curved surface targets and expand the application scope of the irradiation reflection method. It should be noted that the computation scene in Section 3 was a simulated ideal scenario, thus almost completely correcting the measurement errors. In addition to the calculated truncation error, the only remaining error is caused by the process of taking the average value on the reference. For an actual measurement scenario, additional considerations are needed, such as the influences of atmospheric absorption, environmental radiation, equipment errors, and personnel operation. This study only discussed the effect of the single factor of curved surface on measurement results and its correction.

In Section 3.3, set the emissivity of target to 0.5. The test was conducted at different distances l . The emissivity results after correction using the method proposed in this paper are shown in Figure 13. The average relative error and maximum relative error of the corrected emissivity are shown in Figure 14. From Figure 13, we can see more clearly the change in the corrected emissivity result with x ; the closer the target position is to the reference, the smaller the corrected residual error. It can be seen from Figure 14 that the maximum relative error and average relative error of emissivity results decrease significantly with the increase in distance l . This is because when the radiation source is far from the target, the irradiance generated on the target is relatively more uniform and closer to the irradiance on the reference surface, thus reducing the overall error, which is consistent with the analysis results in reference [5].

5. Conclusions

By analyzing the principle of measuring the emissivity with the irradiation reflection method, the cause of errors when using it to measure curved surface objects was identified. Based on this, an angle parameter related to the target surface shape was introduced in the derived formula of the irradiation reflection method, enabling it for analysis and derivation of emissivity measurement for curved surface targets. Next, the formulas for measuring the emissivity under uniform parallel irradiation, point source irradiation, and small-surface source irradiation were obtained. Then, the concept of measurement correction factor was proposed after analyzing the variation rule of the emissivity measurement formulas. A unified form of the correction measurement formula was obtained by introducing the correction factor k , which facilitated practical applications of the theory. Finally, a surface target emissivity measurement scene based on the irradiation reflection method was simulated. The emissivity correction results of targets with different emissivities and different distances between source and target were compared, and the errors of emissivity measurements before and after correction were compared with the true value. The comparison results revealed that the proposed correction method could effectively correct the errors when measuring the emissivity of a curved surface target by the irradiation reflection method, thereby improving the measurement accuracy.

The proposed correction method is based on the original irradiation reflection method, which is compatible with and constitutes an extension of the original theory. The modified irradiation reflection method can be used in measurement scenes of curved surface targets and different types of radiation sources. Combined with the progressive radiance calcula-

tion method in reference [1], it is expected to achieve the emissivity measurement of targets with complex surface shapes, which is of great significance for practical applications and further development of the irradiation reflection method.

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