

Postprint: Coupling of Error Factors in the Concentrating Process of Parabolic Trough Collectors

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Abstract

During actual operation, the concentration process of parabolic trough solar collectors may be influenced by various practical factors including solar incidence angle, installation errors, mirror errors, and tracking errors. This study employs a spatial coordinate transformation method combined with Monte Carlo ray tracing to calculate the heat flux distribution of parabolic trough collectors under individual practical factors and under coupling of multiple practical factors. The results demonstrate that installation errors and tracking errors increase the non-uniformity of the concentrated heat flux, while mirror errors decrease the non-uniformity of the concentrated heat flux; the calculated heat flux distribution under coupled practical factors can provide a basis for analyzing the optical and thermal performance of parabolic trough collectors.

Full Text

Investigation on Coupled Error Factors in the Concentration Process of Parabolic Trough Collectors

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Abstract

During actual operation, the concentration process of parabolic trough solar collectors can be affected by various practical factors including solar incidence angle, installation error, reflector slope error, and tracking error. This study integrates the coordinate transformation method with the Monte Carlo Ray Trace (MCRT) method to compute the heat flux distributions on parabolic trough collectors under both individual and coupled optical errors. The results demonstrate that installation error and tracking error increase the non-uniformity of

the focused heat flux distribution, whereas reflector slope error tends to decrease it. Furthermore, the computed heat flux distribution under coupled optical errors can provide a reliable basis for optical and thermal performance analysis of parabolic trough collectors.

Keywords: parabolic trough collector; concentration process; flux distribution; optical error

Parabolic trough solar collectors (PTCs) represent an important technology for solar thermal power generation. In PTC research, calculating the focused heat flux distribution on the absorber tube surface is often the first critical step. He et al. [1] utilized the Monte Carlo Ray Trace method to compute the ideal focused heat flux for PTCs, demonstrating the practicality of the MCRT approach, which has since been widely adopted [2-3]. However, compared with ideal conditions, the concentration process in real PTCs is influenced by various practical factors including solar incidence angle, installation error, tracking error, and mirror error. Zhao et al. [4] employed spatial coordinate transformations to investigate the effects of absorber tube installation error, tracking error, and solar incidence angle on PTC focused heat flux, while Cheng et al. [5] conducted detailed sensitivity analyses on mirror error and tracking error. Both studies revealed that these practical factors cause significant alterations in the focused heat flux distribution, necessitating comprehensive investigation of heat flux under realistic operating conditions.

Current literature typically computes PTC focused heat flux considering only a single practical factor at a time. In practical applications, however, the concentration process may simultaneously experience multiple influencing factors. This paper first calculates the focused heat flux distribution under individual practical factors and analyzes their effects, then employs spatial coordinate transformations based on the MCRT method to compute the focused heat flux under coupled multiple factors.

1.1 Heat Flux Distribution Simulation Method

[Figure 1: see original paper] presents a schematic diagram of a parabolic trough collector, with the glass envelope omitted for simplicity. The reflector aperture width, focal length, and collector length are denoted by w , f , and L , respectively, with the coordinate origin established at the center of the absorber tube inlet cross-section.

The details of the MCRT method are described in reference [1]. In this method, if the incident ray direction vector is $\mathbf{MATH_0}$ and the reflective surface normal vector is $\mathbf{MATH_1}$, then the reflected ray direction vector $\mathbf{MATH_2}$ is calculated as:

Various practical factors essentially affect the absorber tube position, incident ray direction, or mirror normal direction. Within the MCRT algorithm, these

three aspects operate independently. To investigate each factor's influence, one simply needs to modify the absorber tube position or calculate new vectors using spatial coordinate transformation methods.

1.2 Installation Error

When installation error causes translation of the absorber tube, assuming the new coordinates of the tube centerline in the y and z directions are y and z , respectively, the absorber tube outer wall equation becomes:

$$\text{MATH_3}$$

where r is the outer radius of the absorber tube. Installation error or support structure deformation may also cause the absorber tube to become non-parallel with the focal line. For dual-axis tracking systems, the x -coordinate where a photon is received by the absorber tube equals the x -coordinate of the incident point on the mirror surface (denoted as x). Therefore, once the centerline coordinate equation of the absorber tube is known, the photon arrival position on the tube can still be determined.

For simplicity, assuming the absorber tube inlet cross-section center coordinate is $(0,0,0)$ and the outlet cross-section center coordinate is (L,y,z) , the coordinate equation for the absorber tube outer wall in the plane perpendicular to the focal line becomes:

$$\text{MATH_4}$$

Substituting the new absorber tube coordinate equation (2) or (3) into the MCRT algorithm while keeping other components unchanged yields the non-uniform heat flux distribution on the tube surface under installation error conditions.

For single-axis tracking systems, determining the intersection point between reflected rays and the absorber tube outer wall becomes more complex due to the presence of incidence angle effects. This case is not investigated in the present study.

1.3 Solar Incidence Angle

PTCs employ either single-axis or dual-axis tracking systems to follow the sun's position. Only dual-axis tracking can maintain direct (normal) incidence, but due to structural complexity, single-axis tracking is generally adopted in engineering practice, where the solar incidence angle is often non-zero, as illustrated in [Figure 2: see original paper].

Sunlight ray AB strikes point B on the reflector edge with incidence angle θ , reflects to point C on the absorber tube, where distance CD represents the length of tube segment not receiving reflected sunlight. Reference [6] derived the maximum and minimum values of CD as:

MATH_5

MATH_6

Here, L represents the maximum distance affected by end loss effects, meaning that regions beyond L from the end D experience the total focused heat flux, while tube segments within distance L from the end D cannot receive reflected sunlight at all.

Figure 3: see original paper shows ray 1 as the direct incidence ray calculated by the MCRT method and ray 2 as the oblique incidence ray with incidence angle θ . The coordinate system $O-x' y' z'$ in Figure 3: see original paper is obtained by rotating the $O-xyz$ coordinate system about the y -axis by angle α . The coordinates of ray 1 in this new system, denoted as MATH_7, equal the coordinates of ray 2 in the original $O-xyz$ system:

MATH_8

where \mathbf{A} is the spatial coordinate transformation matrix from $O-xyz$ to $O-x' y' z'$:

MATH_9

Substituting the obtained MATH_10 into equation (1) while keeping other components unchanged yields the heat flux distribution for non-zero solar incidence angles.

1.4 Tracking Error

Tracking error arises from inaccurate tracking, causing deviation in the collector position, as shown in Figure 4: see original paper. Due to tracking error, collector 1 is rotated counterclockwise by angle β relative to its correct position (collector 2). As illustrated in Figure 4: see original paper, the spatial coordinate transformation matrix is:

MATH_11

The modified incident ray coordinates become:

MATH_12

Substituting this result into equation (1) while keeping other components unchanged yields the heat flux distribution under tracking error conditions.

1.5 Mirror Error

Mirror error accounts for reflection errors caused by microscopic defects or macroscopic deformation of the reflective surface. While many types of mirror errors exist, their cumulative effect can be represented by the deviation between actual and ideal mirror normal directions [7]. This deviation angle, when decomposed into x and y components, is assumed to follow identical Gaussian distributions [8]. The actual mirror normal coordinate vector MATH_13 can

be obtained from the ideal mirror normal direction \mathbf{M}_{14} through two coordinate transformations:

$$\mathbf{M}_{15}$$

where \mathbf{A} and \mathbf{B} are calculated using equations (7) and (8). The probability density functions for angles θ and ϕ are identical:

$$\mathbf{M}_{16}$$

Here, σ represents the standard deviation and also the mirror error angle. Substituting the obtained \mathbf{M}_{17} into equation (1) while keeping other components unchanged yields the heat flux distribution under mirror error conditions.

1.6 Coupling of Real Factors

For installation errors, the absorber tube coordinates change compared with the ideal model, and their effects can be considered using equation (2) or (3). For tracking error, mirror error, solar incidence angle, and other factors, the reflected ray direction can be calculated as:

$$\mathbf{M}_{18}$$

where \mathbf{M}_{19} and \mathbf{M}_{20} represent the actual mirror normal and actual incident ray coordinate vectors after accounting for tracking error, mirror error, and solar incidence angle.

It is important to note that since matrix multiplication is not commutative, the order of coordinate transformations cannot be arbitrary. For example, when considering both incidence angle effects and tracking error simultaneously, the actual incident ray coordinate \mathbf{M}_{21} obtained through:

$$\mathbf{M}_{22}$$

yields different results from:

$$\mathbf{M}_{23}$$

Matrix \mathbf{A} converts direct incidence rays to oblique incidence rays, while matrix \mathbf{B} accounts for tracking error. Considering the actual physical process, the heat flux distribution for a single-axis tracking system with tracking error should be calculated using:

$$\mathbf{M}_{24}$$

2 Results and Discussion

The spatial coordinate transformation matrices are employed to simulate and analyze individual practical factors including installation error and solar incidence angle, followed by computation under multiple coupled factors. Since the relative magnitude of heat flux distribution on the tube surface is independent of direct normal irradiance intensity, the local concentration ratio (LCR) is used

in the analysis. The LS-3 parabolic trough solar collector is adopted as the physical model in this simulation, with geometric dimensions and other parameters listed in Table 1. Conclusions regarding other collector models can be obtained through similar analysis.

Table 1 Parameters of the LS-3 PTC

| |
|-----------------------------|
| Absorber tube radius /m |
| Focal length /m |
| Reflector aperture width /m |
| Glass tube transmittance |
| Absorber tube absorptance |
| Reflector reflectance |

2.1 Installation Error Effects

The installation errors in the y and z directions are defined as [4]: $Y = y/w$ and $Z = z/f$. [Figure 5: see original paper] displays the heat flux distribution under translational installation errors. When installation errors reach the millimeter scale, the heat flux pattern already exhibits significant changes. [Figure 6: see original paper] and [Figure 7: see original paper] compare the influence of y - and z -direction errors when both are present. [Figure 6: see original paper] maintains constant Z while varying Y , showing substantial changes in heat flux distribution shape. [Figure 7: see original paper] maintains constant Y while varying Z , revealing relatively smaller changes in distribution shape. Therefore, y -direction installation error has a greater impact than z -direction error, requiring particular attention to minimizing y -direction errors during absorber tube installation.

[Figure 8: see original paper] illustrates the effects of non-parallel installation. With the absorber tube inlet cross-section center at $(0,0,0)$ and outlet cross-section center at $(4,y,z)$ corresponding to $Y = 0.1\%$ and $Z = 0.1\%$, the heat flux distribution is axially non-uniform but can be regarded as a continuous arrangement of translational installation error distributions.

2.2 Incidence Angle Effects

Figure 9: see original paper shows the axial heat flux distribution for dual-axis and single-axis tracking systems under equal direct normal irradiance, with the vertical axis representing total energy absorbed per cross-section. For the single-axis tracking system, the positions of L_1 and L_2 are indicated. The MCRT simulation results agree well with formula calculations, validating the accuracy of the MCRT method for simulating heat flux distribution under oblique incidence. In regions unaffected by end loss effects, each cross-section of the absorber tube receives the same total focused heat flux as under direct incidence with equal irradiance intensity, and can be considered axially uniform. Figure 9: see original paper demonstrates that at the collector tube end, the focused energy received by the absorber tube increases continuously from zero to become circumferentially non-uniform but axially constant.

2.3 Mirror Error and Tracking Error Effects

[Figure 10: see original paper] shows the influence of mirror error on the concentration process. The circumferential heat flux distribution remains symmetric, but mirror error acts to make the focused heat flux more uniform, which helps reduce tube wall temperature differences, with larger errors producing more pronounced effects. Figure 10: see original paper presents the intercept factor variation with mirror error angle in the region unaffected by end loss. When the mirror error exceeds 0.12° , the PTC intercept factor becomes less than 1, a condition that should be avoided.

[Figure 11: see original paper] displays the impact of tracking error on the concentration process. Tracking error causes sunlight to deviate from the direction normal to the reflector aperture plane, increasing heat flux non-uniformity. Figure 11: see original paper shows the intercept factor variation with tracking error angle in the region unaffected by end loss. When tracking error exceeds 0.6° , the intercept factor falls below 1.

2.4 Coupling of Real Factors

[Figure 12: see original paper] presents the heat flux distribution under multiple coupled practical factors: 30° incidence angle, $Y = 0.1\%$, $Z = 0.1\%$, 0.2° tracking error, and 0.1° mirror error. Figure 12: see original paper shows the circumferential heat flux in the region not influenced by end loss effects. Due to the varying magnitudes of different practical errors, the focused heat flux shape exhibits diverse changes. The coupled heat flux distribution can be calculated to provide a basis for optical and thermal performance analysis.

This paper systematically analyzed the effects of practical factors including absorber tube installation error, solar incidence angle, mirror error, and tracking error on PTC heat flux distribution, and computed the PTC heat flux distribution under multiple coupled factors. The following conclusions are drawn:

1. When absorber tube installation errors reach the millimeter scale, the focused heat flux pattern changes significantly. The y -direction installation error has a greater impact on heat flux distribution than the z -direction error, requiring special attention to minimizing y -direction errors during installation.
2. In the region affected by end loss, the focused energy received by the absorber tube increases continuously from zero along the axial direction. Outside this region, the total focused heat flux received by each cross-section equals that under direct incidence with equal direct normal irradiance and can be considered axially uniform.
3. Mirror error makes the focused heat flux more uniform, which is beneficial for reducing tube wall temperature differences, with larger errors producing more obvious effects. In contrast, tracking error increases heat flux non-uniformity, affecting collector safety. When mirror error exceeds 0.12°

or tracking error exceeds 0.6° , the PTC intercept factor becomes less than 1.

4. Due to the varying magnitudes of different practical errors, the focused heat flux shape on the tube exterior changes diversely. The coupled heat flux distribution under realistic conditions can be calculated to provide a reliable basis for optical and thermal performance analysis.

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