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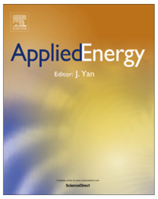

Research on the compensation of the end loss effect for parabolic trough solar collectors

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HIGHLIGHTS

- The optical analysis on the end loss effect of PTC-HNSA is performed in detail.
- A method to compensate the end loss effect of PTC-HNSA is proposed and the optical analysis is made.
- We use typical weather data of some Chinese cities to calculate $\eta_{oel,d}$, $\eta_{oel,y}$, $\eta_{ioe,d}$ and $\eta_{ioe,y}$.
- The applicability conditions of the compensation method is analyzed and discussed.
- Verified the feasibility of the compensation method by experiments with a 5-m long PTC.

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ABSTRACT

In this paper, an optical analysis on the end loss effect of parabolic trough solar collector (PTC) with horizontal north–south axis (PTC-HNSA) is performed, and a method to compensate its end loss effect is presented. The calculation formulae for the optical end loss ratio and the increased optical efficiency (the optical collection efficiency increment of PTC system after this compensation method is used) are derived; the daily optical end loss ratio, yearly optical end loss ratio, daily increased optical efficiency and yearly increased optical efficiency in different latitudes are calculated; the variation of optical end loss ratio and increased optical efficiency with trough's length and latitude angles are analyzed and discussed. It is indicated through the analyses that this compensation method is very applicable for regions with the latitude over 25° (especially over 30°) and short trough collectors. In order to verify the feasibility of the compensation method, a five-meter PTC-HNSA experimental system was built. The increased thermal efficiency of the experimental system is measured, and the result that the experimental value (increased thermal efficiency) substantially agreed with the theoretical value (increased optical efficiency) is gained. All these works can offer some valuable references to the further study on high-efficiency trough solar concentrating systems.

1. Introduction

Solar energy is a sort of energy with low density, intermittent and changing spatial distribution, and is quite different from conventional energy, so it requires more for its collection and application. Among the concentrating solar collectors, parabolic trough solar collector (PTC) is one of the most matured technologies [1]. As one of the middle and high temperature collectors, PTC can be applied in the production and living fields such as thermal generate electricity, industrial process heat, domestic hot water and space heating, air-conditioning and refrigeration, desalination and drying [2–8].

At present, PTC usually adopts single axis tracking. As the sun–earth line is not vertical to earth's axis, the incident rays are generally oblique, therefore, it is inevitable for the PTC to have cosine loss (cosine effect) [2,9–12], and besides, partial end light reflected by one end of trough cannot be gathered to the absorber and also cause end loss effect [6,8,12–14]. The end loss effect of PTC will increase with the increasing of cosine effect, especially for region with high latitude and short PTC, the end loss ratio is relatively high. In application and research, this loss shall be considered and shall be compensated by applicable measures. In some works, although the end loss was considered [6,8,12,13], no further discussion and research on relevant compensation methods were mentioned.

Aimed at the end loss effect of parabolic trough solar collector with horizontal north–south axis (PTC-HNSA), a method that can effectively compensate its end loss effect is presented in this paper.

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Nomenclature

c_p	specific heat (J/kg/°C)
f	focal distance (m)
f_{ar}	focal distance at arbitrary point (m)
h_{av}	average height of end plane mirror (m)
I_0	solar constant
I_b, I'_b	solar beam radiation (W/m^2)
K	absorption constant
L	length of parabolic trough (m)
$L_{oel,ar}$	optical end loss at arbitrary point (m)
$L_{oel,av}$	average optical end loss (m)
L_{pta}	length of focal line formed by sunlight orderly reflected by end plane mirror and parabolic mirror (m)
L_{tpa}	length of focal line formed by sunlight orderly reflected by parabolic mirror and end plane mirror (m)
N	the day number of the year (day)
P_t	solar energy reflected by the parabolic trough (J)
Q, Q'	heat transfer rate (J/s)
T_i, T'_i	inlet temperature (°C)
T_o, T'_o	outlet temperature (°C)
t_S	solar time (h)
v_w	wind velocity (m/s)
w	aperture width of parabolic trough (m)
x, y, z	cartesian coordinates

Greek symbols

β	tilt angle of PTC (°)
δ	declination angle (°)

$\Delta T, \Delta T'$	temperature difference (temperature rise) between outlet and inlet (°C)
η_{ioe}	increased optical efficiency
η_{ite}	increased thermal efficiency
$\eta_{ioe,d}$	daily increased optical efficiency
$\eta_{ioe,y}$	yearly increased optical efficiency
η_{oel}	optical end loss ratio
$\eta_{oel,d}$	daily optical end loss ratio
$\eta_{oel,y}$	yearly optical end loss ratio
η_{oesl}	optical end shade loss ratio
$\eta_{t,ins}, \eta'_{t,ins}$	instantaneous thermal efficiency
θ, θ'	incident angle (°)
θ_z	zenith angle (°)
Θ	rim angle (°)
μ_m	mass flow rate (kg/s)
ρ_p	reflectivity of end plane mirror
ρ_t	reflectivity of parabolic trough reflector
φ	latitude angle (°)
ω	hour angle (°)

Abbreviations

AM	air mass
PTC	parabolic trough solar collector(s)
PTC-HNSA	PTC with horizontal north–south axis

Mainly analyzed the variation of the end loss and compensation effect with the length of trough and latitude, and discussed the applicable latitude scope for the compensation method. A 5-m PTC-HNSA experimental system was built, and the test experiments for the compensation effect were conducted. All these works can offer some valuable references to the further study on high-efficiency trough solar concentrating systems.

2. Analysis for the end loss effect

2.1. Optical analysis

For the PTC-HNSA with the aperture width w, length L and specular reflectivity ρ_t, the solar energy reflected by the parabolic trough will be

$$P_t = wLI_b\rho_t\cos\theta \tag{1}$$

where I_b and θ are respectively the solar beam radiation and the incident angle of sunlight. However, not all solar energy reflected by parabolic trough is gathered on heat absorber tube, and partial energy will be emitted from one end of trough and cause optical end loss (see Fig. 1).

In Fig. 1, Let the equation of edge AOB of parabolic trough be

$$z = \frac{x^2}{4f} \tag{2}$$

where f is the focal distance of parabolic trough, point C is a arbitrary point at parabola AOB, DC is the normal passing point C; light EC is the incident ray parallel to plane yOz, and light CG is its reflective ray. Let the light HC as the incident ray being vertical to trough surface (parallel to axis z) and light CF as its reflective ray, it is obviously that the angle between HC and EC is the incident angle θ. In Fig. 1, FH is vertical to DC, EH is vertical to HC, and GF is vertical to FC, according to geometric relationship, it can be evidenced that $\angle FCG = \angle ECH = \theta$. Let coordinates of point C and focus F respectively as $(x, x^2/4f)$ and $(0, f)$, the distance between points C and F (focal distance of point C) will be

$$f_{ar} = \sqrt{x^2 + (f - x^2/4f)^2} = (x^2 + f^2)/4f \tag{3}$$

It can be gained that the optical end loss caused by sunlight reflected by point C is

$$L_{oel,ar} = f_{ar}\tan\theta \tag{4}$$

The above equation shows that the optical end loss of certain point is related to its focal distance, and it is obviously that the average optical end loss of the whole trough's end is absolutely related with the average focal distance of parabolic trough. In Fig. 1, the coordinates of point A and B are respectively $(-w/2, w^2/16f)$ and $(w/2, w^2/16f)$, and then the average optical end loss of trough's end is

$$L_{oel,av} = \frac{1}{w}\int_{-w/2}^{w/2} f_{ar}\tan\theta\,dx = \frac{w^2 + 48f^2}{48f}\tan\theta \tag{5}$$

where $(w^2 + 48f^2)/48f$ is the average focal distance of parabola AOB. It can be gained that the optical end loss ratio of PTC is

$$\eta_{oel} = \frac{L_{oel,av}}{L} = \frac{w^2 + 48f^2}{48fL}\tan\theta \tag{6}$$

The incident angle θ can be given through the following several formulae [15].

$$\cos\theta = (\cos^2\theta_z + \cos^2\delta\sin^2\omega)^{1/2} \tag{7}$$

$$\cos\theta_z = \cos\varphi\cos\delta\cos\omega + \sin\varphi\sin\delta \tag{8}$$

$$\delta = 23.45\sin[360(N + 284)/365] \tag{9}$$

$$\omega = 15(t_S - 12) \tag{10}$$