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SERI/TR-333-462(CONFERENCE VERSION)
UC CATEGORY: UC-62

MASTER

CONF-791024--8

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OCTOBER 1979

PRESENTED AT THE SOLAR INDUSTRIAL
PROCESS HEAT CONFERENCE,
OAKLAND HYATT HOUSE, OAKLAND, CALIFORNIA,
OCTOBER 31-NOVEMBER 2, 1979

PREPARED UNDER TASK NO. 3471.20

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A Division of Midwest Research Institute

Prepared for the
U.S. Department of Energy
Contract No. EG·77·C·01·4042

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ABSTRACT

Improved parabolic trough concentrating collectors will result from better design, improved fabrication techniques, and the development and utilization of improved materials. This analysis quantifies the relative merit of various technological advancements in improving the long-term average performance of parabolic trough concentrating collectors and presents them graphically as a function of operating temperature for north-south, east-west, and polar mounted parabolic troughs. Substantial annual energy gains (exceeding 50% at 350° C) are shown to be attainable with improved parabolic troughs.

INTRODUCTION

Parabolic troughs are capable of supplying thermal energy over a wide range of temperatures (up to about 350° C) and presently are the leading solar technology in the intermediate temperature range. Several manufacturers have models for immediate application, but the improvement of materials and mechanical components would enhance energy delivery. There is need to reassess the technical merit of improvements that are now possible or would require only moderate development. Those considered in the study pertain to receiver selective coating, reflector properties, and receiver glazing modifications.

ANALYSIS

Methodology

Important to this study was the efficient method of calculation developed by Rabl and Collares-Pereira [1] to predict annual collector energy delivery at a specified location. Collectors are often compared on the basis of peak efficiency curves; a more meaningful basis is the annual energy delivery, because it accounts for off-peak performance and weather variations. This utilizability method involves the calculation of the energy delivery of a parabolic trough for the central day of each month. However, parabolic trough thermal and optical characteristics have been considered in detail so that optical and thermal improvements are validly compared.

A key element of the annual energy calculation is the optimum geometric concentration ratio because it relates thermal and optical performance; i.e., it is the concentration ratio that best balances optical losses with thermal losses. Thus, parabolic trough performance is evaluated for the geometric concentration ratio that maximizes annual energy delivery at each operating temperature.

Eight potentially attractive improvements are evaluated. A reference parabolic trough is defined based on available materials and current technology; it is typical of commercially available parabolic trough concentrating collectors. Each of the eight improvements then define an improved parabolic trough. The annual energy delivery of each improved trough is normalized with respect to the annual energy delivery of the reference trough at the same operating temperature. This ratio of energy delivery is defined as the normalized performance index (NPI). The graphical presentation of NPI versus operating temperature provides an easy determination of the effectiveness of each improvement relative to present technology.

Reference Parabolic Trough and Potential Improvements

The reference trough receiver utilizes a cylindrical glass tube surrounding an absorber tube with a black chrome selective coating. The 90° rim angle reference trough concentrator utilizes a second-surface aluminized-film reflector. Reference trough parameters are:

receiver glazing transmittance	(0.9);
receiver glazing emittance	(0.9);
receiver glazing thickness	[2 mm (0.08 in)];
black chrome absorptance	(0.95);
black chrome emittance	[0.15(100° C), 0.25(300° C)]*;
concentrator hemispherical reflectance	(0.81)**;
reflector nonspecularity (1σ)	(1.6 mrad);
concentrator slope error (1σ)	(6.0 mrad);
tracking error (1σ)	(2.2 mrad); and
receiver/concentrator displacement error (1σ)	(2.0 mrad).

Eight improved parabolic troughs are defined based on the following potential improvements:

(1) selective coating absorptance increase to 0.98;
(2) selective coating emittance decreased to 0.05 (100° C), 0.15 (300° C)*;
(3) back-silvered glass reflector (reflectance increased to 0.95, reflector nonspecularity decreased to 0.5 mrad);
(4) concentrator slope error reduced to 3 mrad;
(5) evacuated annulus receiver;
(6) xenon back-filled annulus receiver;
(7) heat mirror coated receiver glazing (emittance = 0.15, transmittance = 0.94); and
(8) receiver glazing transmittance increased to 0.96.

These improvements are all near-term possibilites. Efforts are underway to increase reflectance through the development of stable, low-cost, back-silvered, thin glass mirrors. On the other hand, fewer efforts are being directed at defining and diminishing concentrator slope errors. Such reductions could result from the use of precision molds, the development of new fabrication techniques, or the development of higher stability substrates. Ways to increase the transmittance of glass have been developed for flat-plate collectors, and these same antireflection coating and etching processes could be adapted to cylindrical

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*Black chrome emittance assumed linear between and beyond these limits.

**Reference trough long-term average reflectance taken from an average of water- and solar radiation-exposed second-surface film samples [2].

line-focus receiver glazings. Selective surface coating development is being actively pursued. Black chrome bath compositions, plating times, and currents are being investigated to improve thermal stability and optical characteristics. Various other coatings are also being developed—some with the potential for very low emittance and therefore reduced receiver heat losses. Other means of decreasing heat losses are receiver glazings coated with heat mirrors and evacuated and back-filled receivers. Back-filled receivers involve filling the annulus between the absorber and surrounding glass with low-conductivity xenon to reduce conduction and convection losses. Development of a parabolic trough receiver that can maintain a vacuum (10^{-3} torr) effectively eliminates conduction and convection within the annulus. A heat mirror coating on the inside surface of the receiver glazing reduces radiation losses from the absorber because of the reduced effective emittance of the glass. However, the solar transmission through the receiver is decreased by the transmittance of the film.

This analysis defines improved performance on the basis of a long-term average, and it must include the effects of accumulated dirt and dust. A long-term average dirt and dust degradation of 6% is included as a modifier to both the concentrator reflectance and glazing transmittance for the reference and improved troughs.

Thermal and Optical Analysis

A thermal model is used to predict heat losses from line-focus parabolic trough receivers. Heat loss is determined as a function of average absorber tube temperature. This eliminates the need to specify the fluid inlet or outlet temperature, rate of flow, and fluid properties.

The thermal model is used to determine receiver heat-loss rates for the reference trough receiver, the evacuated receiver, the xenon back-filled receiver, the heat mirror coated glazing receiver, and the reduced-emittance selective coating receiver. For this study, the absorber tube diameter is held constant at 2.54 cm (1 in). The absorber tube diameter is fixed, but the receiver glazing diameter is sized to minimize the conduction/convection losses. Too small a glass diameter results in excessive conduction losses, whereas too large a glass diameter results in excessive convection losses. For an evacuated receiver, glass diameter sizing is not important because no conduction or convection occurs in the annulus.

Once the effective total optical error is defined, a receiver's heat-loss rate can be used to find the optimum geometric concentration ratio, i.e., the ratio of collector aperture area to absorber tube surface area. The effective total optical error can be calculated by characterizing the sun's size, concentrator slope errors, tracking errors, reflector nonspecularity, and receiver/concentrator displacement errors by Gaussian distributions [3].

After solving for the optimum geometric concentration ratio, the optical analysis is completed with the incidence-angle modifier. The incidence-angle modifier accounts for the variation of optical efficiency with the angle of incidence of incoming radiation. Optical losses are due to the reductions in intercept factor (that fraction of rays incident upon the aperture that reach the receiver) and receiver glazing transmittance and receiver absorptance as incidence angles increase. Our analytical determination of the incidence-angle modifier is in good agreement with published experimental data [4].

RESULTS

Normalized Performance Index

Figures 1a-1c illustrate the performance benefits of parabolic trough improvements in terms of normalized performance indices (NPI) defined for each improvement. The NPI values show how the merits of an improvement vary with operating temperature. The three figures correspond to the three principal tracking orientations: east-west, north-south, and polar.

These results were generated for Denver but can be generally applied to all locations with little error. Sensitivity results indicate increased NPIs for cloudier climates and decreased NPIs for sunnier climates. The variation in NPI from cloudy to very sunny climates has been found to be less than 9%.

Discussion

Substantial performance gains are possible for parabolic troughs due to the increased operating efficiency of the collector and the resulting increase in operating time (an increase in operating efficiency extends operating hours because the threshold value of insolation is lowered).

The performance gains, as represented by the NPI, increase with operating temperature for each of the improvements. This is because of the reduction in the absolute magnitude of trough energy delivery as operating temperature increases. For example, a ten-point increase in collector efficiency represents a larger percentage increase in a collector operating at high temperature (where the annual efficiency may be 30%) than in a collector operating at low temperature (where the annual efficiency may be 60%).

Whereas all the NPI increase with temperature, the rate of increase varies. Improvements associated with increased optical efficiency increase NPI less rapidly than improvements associated with thermal losses; the importance of improvements that reduce thermal losses increase with operating temperature.

At low temperature, thermal losses are small and therefore further reductions are relatively less significant. Optical efficiency improvements dominate in that range; a back-silvered glass reflector has the largest low-temperature performance increase of the improvements studied. An increased receiver glazing transmittance is the second most significant improvement at low operating temperatures. Increasing the selective surface absorptance has only a small impact, because black chrome absorptance has been well developed and little further gain is possible. Mirror reflectance, receiver glazing transmittance, and selective coating absorptance all impact the optical efficiency and for low-temperature operation are the most significant areas in which to introduce improvements.

At higher operating temperatures, thermal losses increase and become more significant to trough performance; they tend to outweigh optical efficiency improvements. Above 150° C, an evacuated receiver shows the largest gain of the improvements that this study considers. A xenon back-filled receiver also significantly increases trough energy delivery with increased operating temperatures. A reduction in concentrator slope error has much the same effect

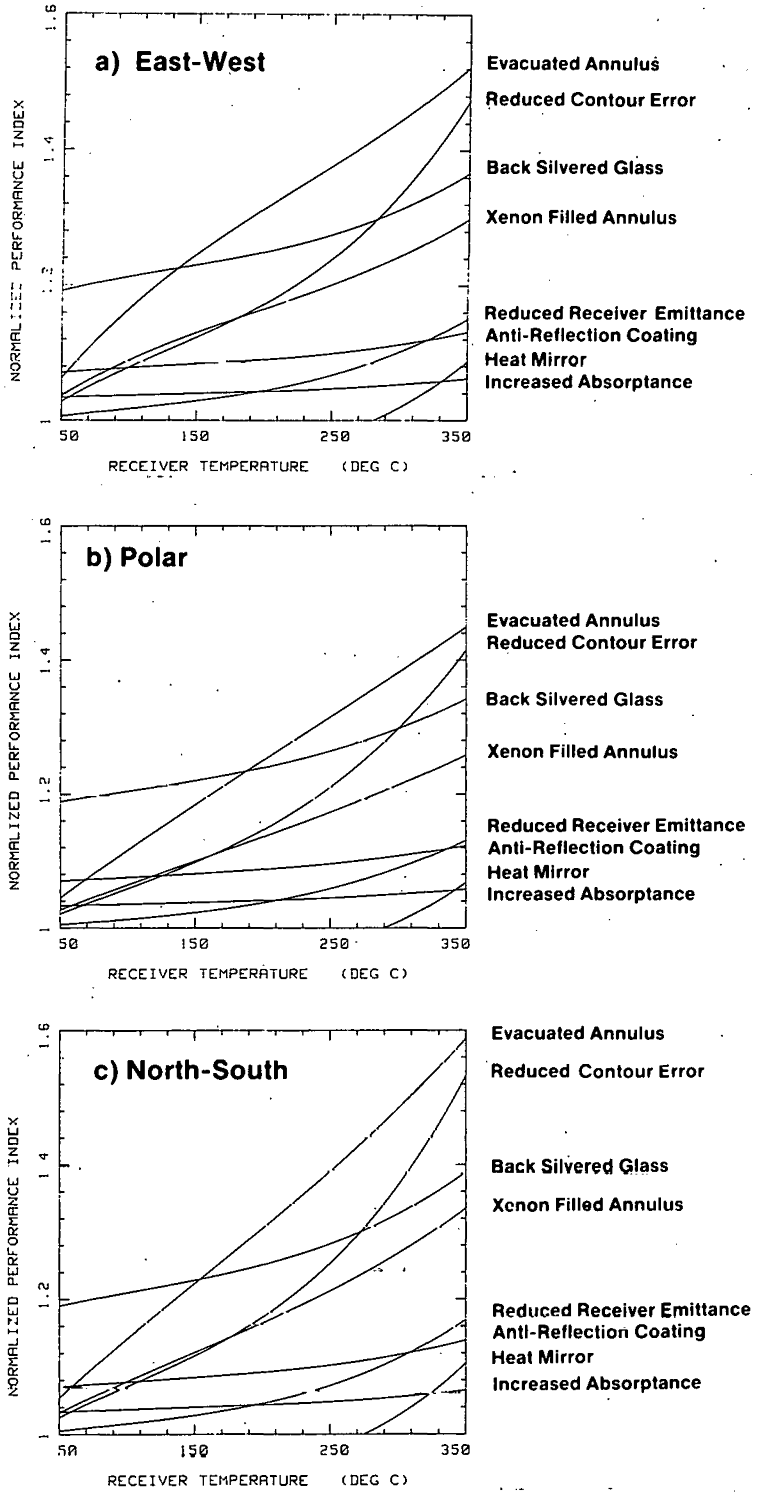

FIGURE 1. PERFORMANCE GAINS FOR IMPROVED PARABOLIC TROUGHS FOR THREE ORIENTATIONS

as thermal improvement because a slope error reduction results in more precise concentrator optics and permits a high concentration ratio trough. Thus, for a given absorber tube size, the optimum aperture area of a parabolic trough increases as slope errors are decreased. This reduces the size of the receiver relative to the concentrator and in effect diminishes thermal losses. Hence, reduced slope error is shown to be a dominant factor in trough performance at high operating temperatures. The merit of heat mirror coated receiver glazings depends strongly on temperature level. Below 275°C, the reduction in thermal losses due to the heat mirror is overshadowed by its reduction in optical efficiency.* Above 275°C, it offers moderate benefit. Decreased selective surface emittance also offers a meaningful performance gain only for high-temperature operation.

The improvements have been considered individually. The performance increase that results from two or more improvements is not the sum of the individual performance increases; one improvement may largely negate potential gains due to another. The performance benefits of combined improvements are considered in the full SERI report [5].

The addition of cost data to the performance data generated in this study will allow the assessment of the improvements on an economic basis. While some of the improvements necessarily involve increased costs, others are potentially low-cost and would add little to total system cost. Further work in this area will address the economic benefits of improved parabolic troughs.

ACKNOWLEDGEMENTS

The authors thank the many individuals from Sandia Laboratories Solar Energy Projects Department and SERI's Materials Branch who supported this project. Special thanks go to Dr. Gideon Yekutieli of the Weizmann Institute of Science, Israel, for his assistance and recommendations.

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*Although using heat mirror coated receiver glazings in conjunction with black chrome is not effective, they may be utilized effectively in place of black chrome or other selective surfaces.