Generation of a Parabolic Trough Collector Efficiency Curve from Separate Measurements of Outdoor Optical Efficiency and Indoor Receiver Heat Loss

Preprint

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Presented at SolarPACES 2010
Perpignan, France
September 21-24, 2010

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Conference Paper
NREL/CP-5500-49304
October 2010

Contract No. DE-AC36-08GO28308

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Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 17721

Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.

GENERATION OF A PARABOLIC TROUGH COLLECTOR EFFICIENCY CURVE FROM SEPARATE MEASUREMENTS OF OUTDOOR OPTICAL EFFICIENCY AND INDOOR RECEIVER HEAT LOSS

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Abstract

The overall efficiency of a parabolic trough collector is a function of both the fraction of direct normal radiation absorbed by the receiver (the optical efficiency) and the heat lost to the environment when the receiver is at operating temperature. The overall efficiency can be determined by testing the collector under actual operating conditions or by separately measuring these two components. This paper describes how outdoor measurement of the optical efficiency is combined with laboratory measurements of receiver heat loss to obtain an overall efficiency curve. Further, it presents a new way to plot efficiency that is more robust over a range of receiver operating temperatures.

Keywords: parabolic trough, efficiency, optical, heat loss

1. Introduction

Collector efficiency is defined as the ratio of energy collected by the working fluid to the direct normal solar radiation incident upon the collector aperture. It is typically determined by testing a collector over a range of high temperatures. Traditionally, the efficiency is plotted vs. the difference between operating temperature and ambient temperature. If the flow rate is sufficiently high, the y-intercept (the efficiency value when there is no heat loss to the environment) on this plot represents the optical efficiency, or the fraction of incident direct normal radiation absorbed by the receiver. The negative slope of the curve is related to the collector heat loss when operating at temperatures greater than ambient. An alternative way to generate the efficiency curve is to use the results of indoor receiver heat loss tests and combine these with an outdoor measurement of collector optical efficiency. This paper describes this approach, provides an uncertainty analysis, and also makes the case that there are advantages to plotting collector efficiency vs. the difference between the operating temperature and the ambient temperature at which the receiver heat loss was measured, as opposed to the difference between operating and ambient temperatures divided by the radiation. Furthermore, dividing this temperature difference by the direct normal radiation raised to an appropriate power can collapse the curves for various radiation values onto a single curve.

2. Results and Discussion

The overall efficiency of a collector can be represented as the optical efficiency, η_o, minus an efficiency penalty term, η', representing thermal losses:

$$\eta = \eta_o - \eta' \qquad \textbf{(1)}$$

where

$$\eta' = \frac{n q_L}{I_{DN} A_{Coll}}. \qquad \textbf{(2)}$$

The heat loss, q_L, is the total heat loss from an individual receiver and n represents the number of receivers contained in a collector module.

In the case of the SkyTrough collector tested at the National Renewable Energy Laboratory (NREL), the optical efficiency for normal solar incidence was measured as 0.773 [1]. The heat loss values, $q_{L,}$ are given as a function of receiver temperature for a prototype Schott PTR80 receiver in Table 1 **[2]**. Accounting for the fact that the SkyTrough uses three such receivers, and combining the optical and thermal efficiency values using Equation 1, the overall efficiency curves for direct normal radiation values of 1000, 800, and 600 W/m^2 and an ambient temperature of 25°C are plotted vs. test temperature difference in Figure 1.

Absorber (°C)	99	154	200	240	242	293	355	401	406	449	449
Heat Loss (W/m)	12	26	43	66	68	110	191	278	490	412	564

Table 1. Heat losses for PTR80 receiver [2]

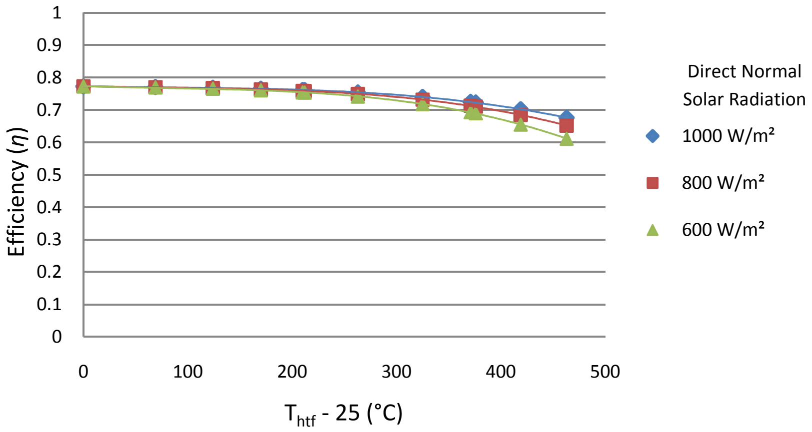


Figure 1. SkyTrough normal incidence efficiency from combining collector optical efficiency and receiver heat loss results, for three radiation values.

The Hottel-Whillier-Bliss equation, originally developed for flat plate collectors with high convective heat losses, does not accurately fit the data even with a second order term in temperature. This is because the major thermal resistance associated with the heat loss for a high-temperature parabolic trough corresponds to the radiation across the receiver vacuum annulus. Additionally, the traditional method of plotting efficiency versus the difference between the fluid temperature and ambient temperature, results in an efficiency curve that is only valid for one ambient temperature. Two identical collector modules with the same delta T but different operating temperatures will exhibit different efficiencies. The heat loss is a function of the absorber temperature raised to the fourth power minus the glass temperature raised to the fourth power, and therefore efficiency does not vary with the square of the temperature difference. As the receiver temperature increases, so too does the glass temperature and thus the heat loss goes up more slowly than the fourth power.

Parabolic trough collector efficiency is much more dependent on the operating temperature than the ambient temperature. By plotting efficiency vs. the difference between the operating temperature and the ambient temperature at which the receiver was tested, one obtains a plot that, while it is only strictly accurate at the ambient temperature at which the receiver was tested (which can be standardized), yields quite accurate results over a wide range of ambient temperatures. Plotting efficiency vs. the difference between the operating temperature and lab ambient rather than the operating temperature and solar field ambient temperature achieves two things. First, it makes clear what ambient temperature the receiver was tested at. Second, it preserves a useful feature of the Hottel-Whillier-Bliss equation in that the y-intercept is equal to the collector optical efficiency, i.e., the efficiency with no heat loss.

The overall efficiency data in Figure 1 is fit accurately (R^2=0.9993) by a cubic polynomial of the form

$$\eta = A_3 x^3 + A_2 x^2 + A_1 x + \eta_o \qquad \textbf{(3)}$$

where $\boldsymbol{x}$ is the difference between the heat transfer fluid temperature and the receiver test temperature and the coefficients, A_3, A_2, and A_1 are given in Table 2.

I_{DN} (W/m^2)	R^2	A_3	A_2	A_1	$\boldsymbol{\eta_o}$
1000	0.9997	$\mathbf{-1.41\times10^{-9}}$	$\mathbf{3.26\times10^{-7}}$	$\mathbf{-5.84\times10^{-5}}$	0.773
800	0.9997	$\mathbf{-1.76\times10^{-9}}$	$\mathbf{4.08\times10^{-7}}$	$\mathbf{-7.03\times10^{-5}}$	0.773
600	0.9997	$\mathbf{-2.34\times10^{-9}}$	$\mathbf{5.44\times10^{-7}}$	$\mathbf{-9.74\times10^{-5}}$	0.773

Table 2. Coefficients for cubic fits to overall efficiency curves vs. ΔT

The temperature difference in the abscissa can be either the absorber temperature minus lab ambient or the expected fluid temperature minus lab ambient. In the laboratory, absorber tube temperature is measured via thermocouples on the inside of the absorber tube and so is well known. Modeling the heat loss indicates that there is only a 0.2 °C temperature difference between the inner and outer surface of the tube during the electric resistance heating. In an actual collector, solar radiation will heat the outside of the tube slightly higher than the inside.

Absorber temperature will generally not be known in the field; thus it is advantageous to use the fluid temperature, which will be known in an actual installation. If efficiency is plotted against fluid temperature minus lab ambient, the correction from absorber temperature can be modeled. The internal heat transfer coefficient for an operating receiver with fluid flow is sufficiently high that the average outside tube temperature will be only about 6 °C higher than the fluid temperature. Another issue, however, is that in an operating collector solar flux non-uniformity will result in a circumferential temperature gradient around the receiver tube. Eck et al. [4] show an increase in heat loss of up to 3% due to this effect. In Figure 1, we have made the small correction from measured absorber temperature to average fluid temperature and plotted the efficiency vs. the difference between fluid temperature and lab ambient, but have neglected the increase in heat loss due to the circumferential temperature gradient. The trend lines shown are third order polynomials, which provide an excellent fit.

The various radiation curves can be collapsed into a single curve by dividing the temperature difference by direct normal radiation, I_{DN}, raised to a fractional power. This eliminates the uncertainty associated with trying to interpolate between different radiation curves. For the SkyTrough using a Schott PTR-80 receiver, a non-linear regression shows the best fit exponent to be 0.33. Plotting efficiency vs. $(T_{htf} - 25)/I_{DN}^{0.33}$ collapses the three radiation curves into one as shown in Figure 2. The cubic fit given in Equation 4 has an R^2 value of 0.9994.

$$y = -1.26 \times 10^{-6}x^3 + 3.02 \times 10^{-5}x^2 - 6.24 \times 10^{-4}x + 0.773 \qquad \textbf{(4)}$$

The best fit exponent on I_{DN} will vary with receiver. (For example, when an older model receiver from a different manufacturer is assumed in place of the PTR80, the exponent is 0.38.) For other collectors and receivers, if it is desired to collapse the radiation curves into a single curve, we recommend performing a non-linear regression to simultaneously determine the best-fit polynomial (third or fourth order) coefficients and the exponent on I_{DN}.

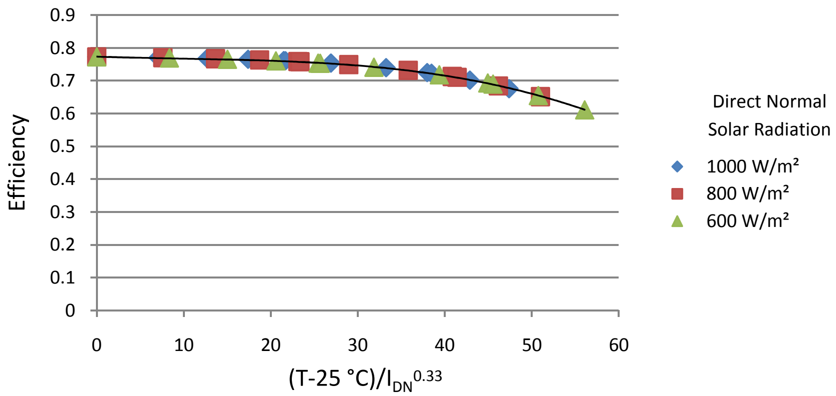
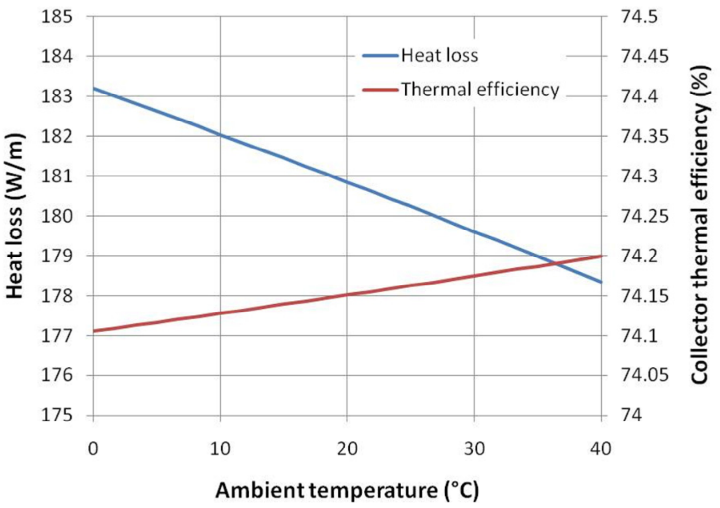


Figure 2. SkyTrough normal incidence overall efficiency with three radiation values collapsed onto a single curve.

A receiver tested indoors is typically tested at a specific ambient temperature, a sky temperature equal to ambient temperature, and zero wind speed. All three of these quantities will vary outdoors (and are difficult to control in an outdoor test). The impacts of ambient temperature, sky temperature, and wind speed on efficiency were investigated using a collector model that NREL developed in Engineering Equation Solver [3]. Figure 3 shows the receiver heat loss and collector thermal efficiency as a function of ambient temperature. These simulations were performed using a 6 m aperture trough with an entering heat transfer fluid temperature of 350°C.



Increasing the ambient test temperature from 25°C to 40°C decreases the heat loss by only 1% and decreasing the ambient temperature to 0°C increases the heat loss by only 2%. Because the heat loss is only a couple percent of the energy collected, such a small change in heat loss will typically change the efficiency by only 0.2% or less.

The impact of changes in sky temperature is even less as shown in Figure 4. When a detailed collector model is run at different sky temperatures, it shows that, for the case of a new receiver tube, reducing the sky temperature by 30°C will reduce the collector efficiency by less than 0.1%.

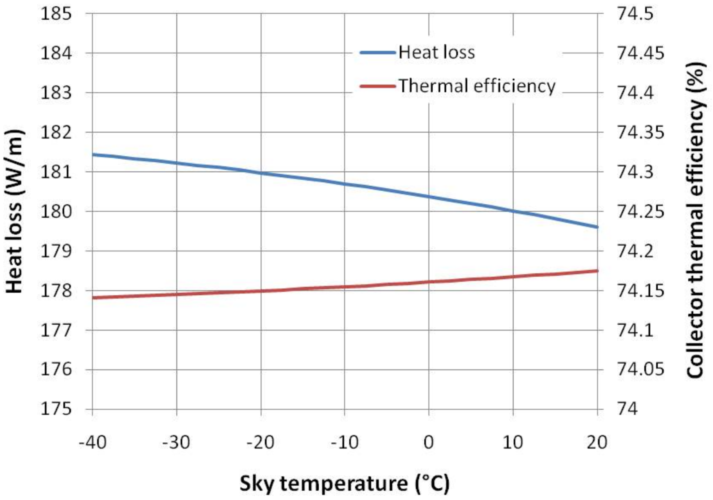


Figure 4. Impact of sky temperature on receiver heat loss.

Finally, the impact of wind speed on heat loss is shown in Figure 5. Compared to an indoor wind speed of zero, wind speeds of 10 m/s can increase the heat loss about 4%, which would reduce efficiency by 0.4% or less. The advantage of using the indoor test results for the heat loss is that the wind speed under test conditions (as well as the ambient temperature and sky temperature) are constant during the test and thus well controlled and well known. A model can then be used to correct the heat loss for varying conditions.

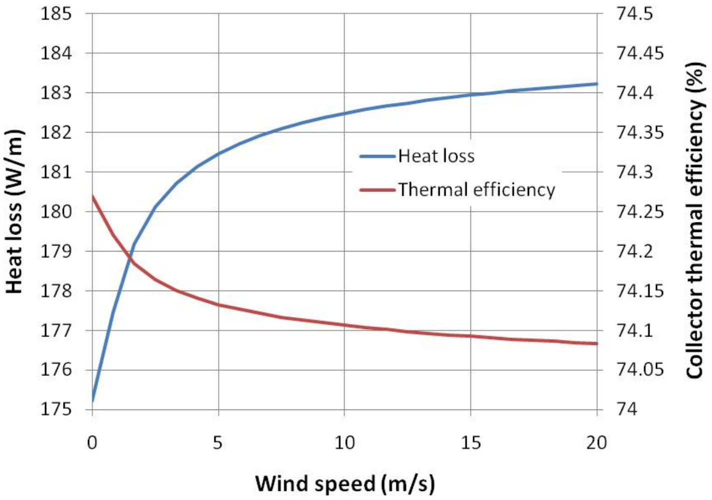


Figure 5. Impact of wind speed on receiver heat loss

3. Experimental Uncertainty

Developing separate tests for optical efficiency and heat loss provides an opportunity to focus each experiment individually to minimize its experimental uncertainty. Because our outdoor test loop used to measure optical efficiency operates only at ambient temperature, instrumentation can be chosen to take advantage of use with water and glycol-water mixtures and minimize uncertainty at this low temperature. The following steps were taken to ensure high accuracy:

- Mass flow rate is directly measured using the highest accuracy (±0.13%) Coriolos-type flowmeter designed for use in water and water-glycol mixtures. Measuring mass flow rate directly instead of volumetric flowrate eliminates any errors associated with uncertainty in fluid density, which depends on temperate and glycol-water mixture ratio.
- High-precision calibrated platinum RTDs (±0.05°C) with large immersion depth are used to measure inlet and outlet temperatures. Signal conditioning is done in the field to eliminate errors associated with lead wire resistance. The delta T between receiver inlet and outlet is zeroed under no-sun conditions.
- The test facility is located immediately adjacent to NREL's Solar Radiation Research Laboratory, which takes readings of direct normal solar radiation that are regularly checked against a calibrated cavity radiometer. This allows a precision error of ±0.43%.
- Operation at ambient temperature allows for pure water to be used as the heat transfer fluid in non-freezing conditions, and the heat capacity of pure water is very well characterized. For freezing conditions, a mixture of propylene glycol and water is used and the exact mixture is determined via an Atago digital refractometer. The specific heat precision error for a mixture is ±0.19%.

A separate propagation of bias and precision errors and combining them using the root-sum-square results in an uncertainty of ±1.43% of the optical efficiency value.

Similarly, high accuracy is obtained in the indoor measurement of receiver heat loss:

- Electric heaters are used to heat the tubes and power is measured with transducers having an accuracy of ±0.5% of full-scale. Different scale transducers are used for different temperatures to achieve the highest accuracy
- Guard heaters are used at each end of the receiver to provide a zero temperature gradient at the end and thus an adiabatic edge condition. In this way the receiver heat loss is representative of a large solar collector assembly as opposed to a single module
- An array of special-limit type K (chromel-alumel) thermocouples is used to obtain absorber surface temperatures. The low lead wire thermal conductivity, along with careful installation, minimizes lead wire conduction loss, which is critical for obtaining an accurate surface temperature measurement
- Data is taken under steady-state conditions, defined as center of glass and absorber temperatures have remained unchanged for 15 minutes.

As a result of these measures, receiver heat loss is determined to within ±8 W per meter of receiver length, which corresponds to about 5% of a typical operating receiver heat loss. Because heat losses from receivers are so low, attempting to determine this quantity by measuring the small temperature drop across an individual collector module at operating temperature under no-sun conditions results in high experimental uncertainty. The 5% uncertainty we obtain in receiver heat loss translates to an uncertainty in the thermal component of collector efficiency of only ±0.13%.

Combining the optical and thermal efficiency uncertainties results in an overall uncertainty in collector efficiency (at typical operating conditions) of ±1.44%, which is clearly dominated by the uncertainty in the optical efficiency measurement.

4. Conclusions

Obtaining an overall efficiency curve for a high-temperature parabolic trough collector by combining a laboratory measurement of receiver heat loss with an outdoor measurement of collector optical efficiency is a practical alternative to outdoor testing over a range of temperatures and even offers some potential advantages. Experimental design can focus on achieving minimum uncertainty for each of the two quantities. Parameters affecting receiver heat loss such as ambient temperature, sky temperature, and wind speed are constant and well characterized for indoor receiver testing. Measuring optical efficiency with pure water as the working fluid allows the specific heat to be well characterized. The use of water at low temperature also allows direct, high-accuracy measurement of fluid mass flow rate.

In addition, the approach recommended here of plotting efficiency vs. the difference between operating temperature and laboratory ambient test temperature (as opposed to the difference between operating temperature and ambient temperature) provides a more accurate result over a range of ambient temperatures and yet preserves the feature that the y-intercept is equal to the optical efficiency. Further, dividing the abscissa by the direct normal radiation raised to a fractional power (determined via regression) and plotting the data as a third- or fourth-order polynomial allows for the various radiation cases to be collapsed onto a single curve. The method described here is applicable to modern high-concentration parabolic trough collectors employing evacuated receiver tubes and used for electricity generation.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
October 2010

2. REPORT TYPE
Conference Paper

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Generation of a Parabolic Trough Collector Efficiency Curve from Separate Measurements of Outdoor Optical Efficiency and Indoor Receiver Heat Loss: Preprint

5a. CONTRACT NUMBER
DE-AC36-08GO28308

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
C. Kutscher, F. Burkholder and K. Stynes

5d. PROJECT NUMBER
NREL/CP-5500-49304

5e. TASK NUMBER
CP09.1001

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/CP-5500-49304

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*

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15. SUBJECT TERMS
parabolic trough; efficiency; optical; heat loss

16. SECURITY CLASSIFICATION OF:

a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
Unclassified	Unclassified	Unclassified	UL	

19a. NAME OF RESPONSIBLE PERSON

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