Measuring the Optical Performance of Evacuated Receivers via an Outdoor Thermal Transient Test

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MEASURING THE OPTICAL PERFORMANCE OF EVACUATED RECEIVERS VIA AN OUTDOOR THERMAL TRANSIENT TEST

Charles Kutscher[1], Frank Burkholder[2], Judy Netter[3]

Abstract

Evacuated receivers used with parabolic trough collectors can be characterized in terms of their heat loss and their optical efficiency. The latter is the fraction of sunlight striking the receiver tube that is absorbed. It is equal to the product of the transmittance of the glass cover (τ) and the absorptance of the absorber surface (α). This paper describes an outdoor transient test method for measuring the τα product. The receiver is filled with cold water and exposed to outdoor solar radiation. The slope of the temperature vs. time curve is taken symmetric about the point at which the average glass temperature is equal to the average absorber temperature (i.e., the point at which there is no heat loss or gain from the absorber tube), and this is used to determine the τα. This method has the advantage of using the actual solar spectrum and has an uncertainty of ±2%. Preliminary measurements of an actual receiver tube yield a τα that is reasonably close to the manufacturer's specifications.

1. Introduction

Modern parabolic trough solar collectors operate with high fluid temperatures to provide the heat input to Rankine steam power cycles. High performance is achieved via the use of a receiver tube with a selective surface having a high absorptance for incoming short-wave solar radiation and a low emittance for outgoing long-wave infrared radiation, as well as an evacuated glass envelope around the receiver tube to essentially eliminate convective and conductive heat losses. NREL [1], DLR, and receiver manufacturers measure heat loss in the laboratory by supplying electric resistance heat and measuring the heat input at steady-state conditions. NREL measures the overall optical efficiency of a trough collector on an outdoor test stand [2]. The optical efficiency of an evacuated receiver is the product of the transmittance of the cylindrical glass envelope and the short-wave absorptivity of the receiver coating. Techniques are available for measuring these quantities separately for an unassembled receiver, but this is not easily done for the final assembled product. DLR measures the optical efficiency of an assembled and evacuated receiver using a steady-state method in an indoor solar simulator [3]. This paper describes a new method that determines overall receiver optical efficiency by exposing a fluid-filled, pre-cooled receiver to one sun outdoors and measuring the slope of the temperature curve at the point where the average absorber temperature is equal to the average glass envelope temperature (that is, the point at which there is no heat gain or loss from the absorber). The use of an aperture or masking device allows testing with either total solar irradiance or direct normal irradiance. This transient test method offers the potential advantages of simplicity, high accuracy, and the use of the actual solar spectrum.

2. Methodology

The optical efficiency of a receiver can be represented as τα, the product of the transmittance of the glass envelope, τ, and the short-wave solar absorptivity of the receiver coating, α. To conduct a transient heat transfer test on a receiver with the goal of measuring τα, the receiver tube is first filled with cold water at a temperature below that of the ambient air. The receiver is then exposed to one sun (either total solar irradiance or direct normal irradiance). By

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orienting the receiver tube along a North-South line and at an angle to the horizontal corresponding to the zenith angle at solar noon, tests performed around noon result in the sun striking normal to the collector, although any cosine effect can be accounted for in the incident radiation calculation. The water is circulated during the test to maintain a uniform temperature.

A number of temperature sensors (e.g., thermocouples) are positioned at various locations to determine the average temperature of the mass as a function of time and assess its uniformity. The better the uniformity, the higher the confidence that the measured average temperature represents the bulk temperature. The value of $\tau\alpha$ can be experimentally determined as follows:

$$\tau\alpha = MC \cdot \frac{\Delta T}{\Delta t} \cdot \frac{1}{IA} \tag{1}$$

where M = the mass of the receiver tube and its contents (kg)
C = the average (mass-weighted) heat capacity of the receiver tube and its contents (J/kg-°C)
ΔT = the change in mass temperature over a small time period centered around the point at which the average absorber temperature is equal to the average glass temperature (°C)
Δt = the time period over which the slope is determined (sec)
I = the solar radiation to which the receiver is exposed, either total or direct normal (W/m^2)
A = the area of the receiver tube exposed to the radiation (m^2)

The receiver glass temperature is higher than ambient temperature because it absorbs some sunlight. When the absorber temperature is at the average glass temperature, there is no heat loss or gain from the absorber tube and equation 1 holds. By determining the slope centered on the point at which the average absorber temperature equals the average glass temperature and inserting it into equation 1, the $\tau\alpha$ product can be determined. An example of a plot generated from a simple model is shown in Figure 1. Note that the absorber temperature leads the fluid temperature but that the slopes of the two curves are virtually identical. Note also that the plots are fairly linear, but are slightly concave downward due to the fact that the receiver loses more heat to the ambient as its temperature goes up. To obtain the best data, one wants a high value or IA (that is, high irradiance and a large aperture), so that as one deviates from the zero heat transfer point, the heat exchange term is small compared to the solar input term. This results in high linearity, and hence latitude in where the slope is measured (as there is some uncertainty in determining the average glass and absorber temperatures and hence the zero point location). One also desires that the radiation be steady on either side of the zero heat transfer point so that the slope measured over a finite time interval symmetric about the zero point will closely match that at the zero point.

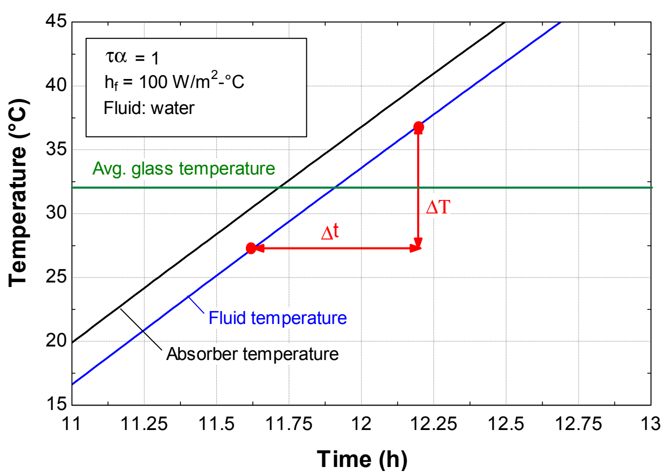

Figure 1. Example temperature plot for a transient experiment showing absorber and fluid temperatures vs. time.

An uncertainty analysis indicates that the various parameters can be determined with the following uncertainties:

Table 1. Uncertainties in the parameters

Component	Variable	Uncertainty in measurement
Thermal capacitance of system	MC	±1 %
Temperature rise	ΔT	±0.2°C
Testing period	Δt	±1 s
Insolation on absorber	I	±1.5 %*
Absorber aperture	A	±0.5 %

Combining the various uncertainties (see Section 5) results in an overall uncertainty in $\tau\alpha$ of ±0.02. The error can be further reduced if a standard receiver is available.

3. Apparatus

The test stand (see Fig. 2) is designed to simultaneously measure the performance of two test receivers side-by-side with a standard reference receiver. The $\tau\alpha$ of each test receiver can then simply be determined by multiplying the $\tau\alpha$ of the standard receiver by the ratio of the temperature vs. time slope for the test receiver to that of the standard receiver. This improves the overall accuracy (assuming $\tau\alpha$ for the reference receiver is known to high accuracy) because the irradiance (which has the largest uncertainty of the measurements) is the same for the reference and test receivers and so need not be measured. Where a standard receiver is not available, equation 1 is solved. Each receiver under test is surrounded by a shroud to prevent radiation reflected off the ground from striking the receiver and to allow only direct normal irradiance (DNI) to strike the absorber tube. Our current shroud uses a black channel in the front through with the DNI passes. Because some solar radiation can reflect off that channel and because the channel can get warm and emit infrared radiation, we intend in the future to replace the channel in the shroud with a simple slit.

Figure 2. a. Schematic of test rig showing 3 receivers. b. Photo of actual shrouded commercial receiver under test. (*Photo: C. Kutscher)*

A pump is used to circulate water inside the absorber tube to achieve uniform temperature. The pump at the top of each receiver tube pumps water down a small feeder tube inside the steel absorber tube and the water returns in the annular region between the feeder tube and the absorber tube. Thermocouples are used to determine the temperatures of the water and absorber tube at various locations as shown in Figure 3.

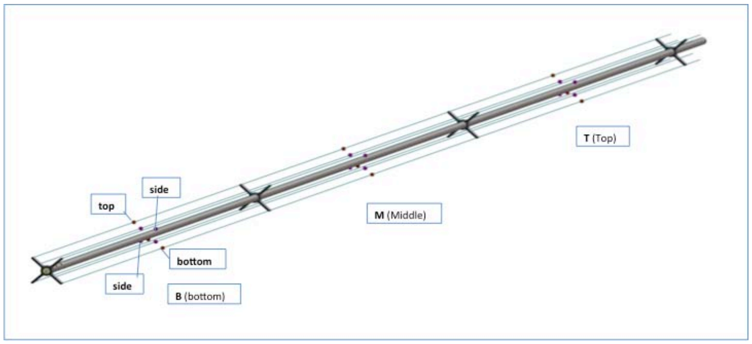

Figure 3. Locations of thermocouples inside receiver tube.

To obtain an accurate slope corresponding to the zero heat transfer point, it is important to determine the average glass and absorber temperatures. For the data taken to date, we measured the front of the glass and assumed that the back of the glass is at ambient temperature (due to the low circumferential heat conductance around the thin glass). The average glass temperature is taken as the average of the front glass temperature and ambient. Because we have found that the τα result is more sensitive to the exact temperature at which that slope is centered than originally expected, we intend to improve the experimental apparatus by installing more glass temperature measurements to obtain a better average glass temperature. We also plan to improve our measurement of average absorber temperature.

4. Results and Discussion

The test apparatus is located at NREL's mesa top test facility in Golden, Colorado. Because of unusually rainy weather in the summer of 2011, there were few long periods of steady DNI. However, test data taken on July 28 with less-than-ideal solar radiation are reported here. A commercial evacuated receiver tube was exposed for 200 minutes to an average of 928 W/m^2 of direct normal insolation. The variation of the DNI can be seen in Figure 4. This shows that there were some downward spikes in the radiation as clouds passed overhead.

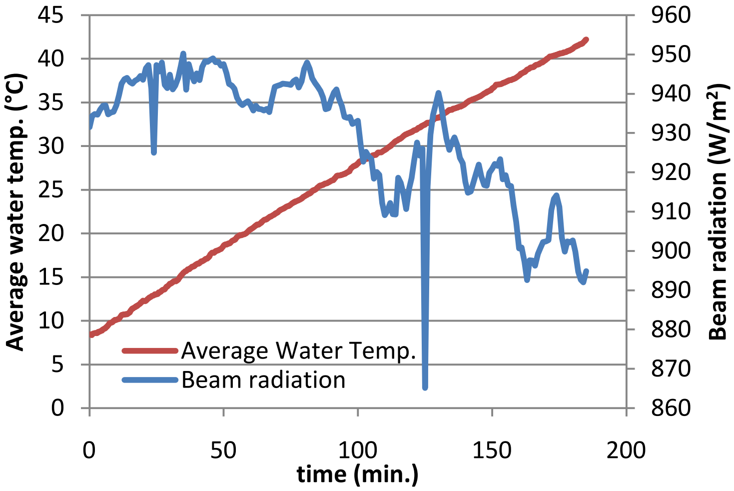

Figure 4. DNI and average water during the test period.

A plot of water temperature vs. time for the various temperature sensors throughout the water is shown in Fig. 5. Three general observations can be made. First, there is very good temperature agreement at all of these locations. Second, and more importantly, the slopes of the temperature vs. time curve are in close agreement at all locations. The curves appear fairly linear, although the slope is still somewhat sensitive to the specific time where it is measured.

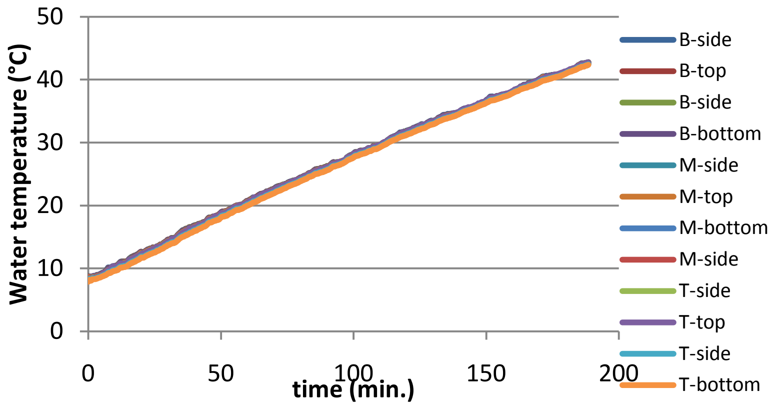

Figure 5. Time-temperature profiles at 12 different locations in the water.

In general, small variations in irradiance can put jiggles in the temperature curve, and a better slope value can be determined if we smooth the curve using a running average. Figure 6 shows plots of average water temperature vs. time for running averages ranging from 10 seconds to 15 minutes for data taken with an aperture mask. These curves all have roughly the same average slope. The longer running averages are shifted to the right, reflecting the fact that it takes some time to accumulate the running average. In choosing a slope we want to pick two points symmetrically on either side of the point at which the average absorber temperature equals the average glass temperature. If we use the top curve, the small jiggles in that curve mean that the slope is sensitive to the locations of the points chosen. On the other hand, if we use the much smoother lower curve, the slope is less sensitive to the selection of end points.

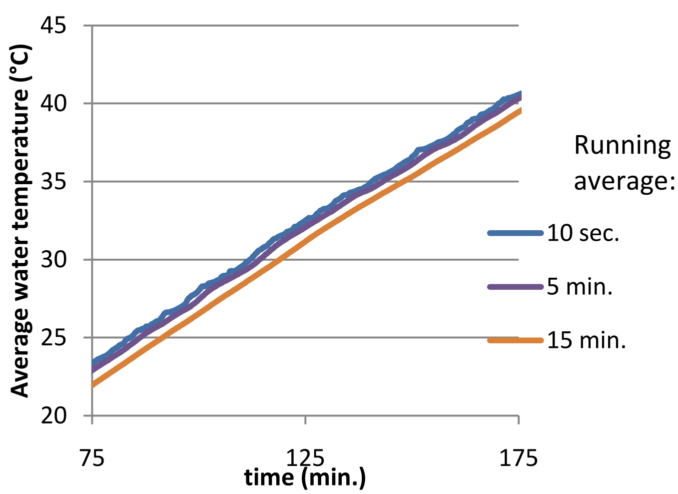

Figure 6. Average water temperature vs. time curves for different running averages.

To calculate $\tau\alpha$ from equation 1, one needs not only the slope of the temperature curve at the zero heat transfer point (as well as the radiation and receiver aperture area through which that radiation passes) but also the MC product. In calculating the MC product, one must take into account all the thermal mass being heated. Table 1 shows the thermal capacitance values of the various components undergoing transient heating.

Table 2. Thermal capacitance values.

Water	57169.6	J/C	87.8%	of total
Absorber steel	6702.7	J/C	10.3%	of total
Center tube	530.0	J/C	0.8%	of total
Wire rope	5.0	J/C	0.0%	of total
Cross supports	9.6	J/C	0.0%	of total
TC wire + sheating	634.0	J/C	1.0%	of total
Plug in bottom	42.7	J/C	0.1%	of total
Total	65093.5	J/C		

This shows that the thermal capacitance is dominated by the recirculating water in the receiver tube, which represents 87.8% of the thermal capacitance. When this is combined with the thermal capacitance of the absorber pipe, these two components account for 98.1% of the total thermal capacitance. As the thermal capacitance (mass times specific heat) of these two quantities is well known, there is high confidence in the total thermal capacitance value.

With the values of MC and the integrated value of the DNI during the relevant portion of the test, we can now pick the slope from 15-minute running average curve of temperature. With the average glass temperature estimated as 32°C, the average water temperature reaches this value at minute 125. (For these initial measurements, we did not have an adequate measurement of absorber temperature and so used the water temperature, but this will be rectified in the future.) Table 2 shows calculations for $\tau\alpha$ using slopes obtained from six different time intervals of varying length, but all centered on the time of 125 minutes. Also shown is the standard deviation for each as well as twice the standard deviation, which would correspond to the 95% confidence value.

Table 3. Results for $\tau\alpha$ using test time intervals of different lengths.

Tstart	Tend	ta ave	std	2*std
75	175	0.9494	0.011	**0.023**
80	170	0.9475	0.012	**0.024**
85	165	0.9504	0.013	**0.025**
90	160	0.9504	0.014	**0.027**
95	155	0.955	0.015	**0.030**
100	150	0.9575	0.017	**0.035**
	Average:	**0.952**		

The results indicate a value of 0.95 ±0.027. Whereas the result is not very sensitive to the length of the time interval, it is more sensitive to the location of the center of that interval. We can examine this by evaluating the impact of the glass temperature being 5°C lower or 5°C higher than assumed. If instead of 32°C, the average glass temperature were 27°C, the steeper slope at that part of the curve would yield a $\tau\alpha$ value of 1.004. If the average glass temperature were 37°C, a $\tau\alpha$ value of 0.894 would result. The manufacturer of the receiver tube quotes a transmittance value of 0.97 and an aborptance value of 0.96. The product of these is 0.931. While our measured value of 0.95 is within 0.02 of the manufacturer's value, it is quite dependent on the assumed average glass temperature. It is important to have accurate measurements of both the glass and absorber temperatures to determine the zero heat transfer point. This is especially important if the radiation is not steady, as was the case with the data reported here.

5. Experimental Uncertainty

The major sources of experimental uncertainty are in the measurement of the solar radiation and the temperature rise. The experiment is located immediately adjacent to NREL's Solar Radiation Research Laboratory (SRRL). SRRL estimates a combined random and systematic error for these measurements of ±1.5%. As the direct normal irradiance is on the order of 1000 W/m2 and the diffuse radiation is less than 10 percent of that, the error in diffuse radiation is less than one-tenth that for the direct normal. The accuracy of the measurement of the temperature rise is very high because the same thermocouples are used at the two points in time. Also, the temperatures at the two points in time are very close, differing by only about 15 degrees Celsius, so one expects very little difference in thermocouple behavior. Also, we average the results from many different locations. Thus there should be virtually no systematic error in the temperature rise measurement. Random error is minimized by taking a large number of samples and is estimated at only 0.1C. When all of the errors are combined using a root-sum-square method, the total error in $\tau\alpha$ is estimated at ±0.015.

An alternative way to evaluate this is to apply all the various uncertainties and vary the values using a Monte Carlo approach. This was done using Matlab, and the results (based on the 32°C assumed glass temperature) are shown in Figure 7. Using the 2σ (95% confidence) result, this shows a value of 0.95±0.02, which is in close agreement with the other approach.

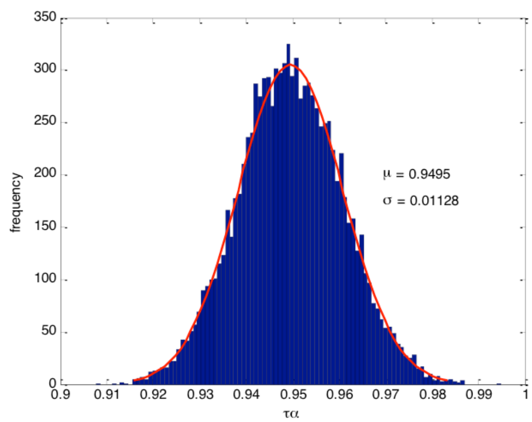

Figure 7. Monte Carlo uncertainty analysis, in which the various parameters in equation 1 are varied in Gaussian distributions according to their individual uncertainties and $\tau\alpha$ is calculated in each case.

It is important to note, however, that neither calculation properly takes into account the uncertainty in measuring the glass and absorber temperatures in order to accurately locate the zero heat transfer point, and this needs to be explored further.

6. Conclusions

As new low-cost receivers are developed, it is important to understand not just the heat loss performance but also the optical efficiency, i.e., the product of the glass transmittance, τ, and the absorber absorptance, α. The transient thermal test method described in this paper offers a way to measure the $\tau\alpha$ product of a receiver with potentially high accuracy. The temperature rise of the receiver during a transient test can be measured with higher accuracy than the outlet minus inlet temperature difference in a steady-state test. Also, outdoor solar radiation can be measured with high accuracy and an outdoor test provides results that correspond to the true wavelength spectrum that the receiver will operate under in actual practice.

7. Future Work

Because results have shown that the slope calculation (and hence the value of $\tau\alpha$) is sensitive to the location of the zero heat transfer point, especially when the irradiance is not steady, we intend to analyze this effect using a heat transfer model. We will also install additional instrumentation to obtain a better average glass temperature and absorber temperature to allow us to more accurately determine when these temperatures are equal. The mass of water was obtained from a volumetric measurement. We intend to explore more accurate mass measurements of the other components. We will improve the shroud to minimize any heat transfer of reflected radiation between the shroud and the receiver while maintaining a large value of IA, which minimizes the impact of any heat exchange. We will evaluate the repeatability from additional tests and we also plan to test other tubes, in particular those that have been tested by other laboratories.

Acknowledgments

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