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Thermal efficiency analysis of SkyFuel's advanced, large-aperture, parabolic trough collector

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Abstract

SkyFuel has empirically established the thermal efficiency of the *SkyTrough® DSP*: an advanced, low-cost parabolic trough collector recently developed by SkyFuel, Inc., and funded in part by DOE grant DE-EE0003584.000. A full-scale demonstration module has been built at SkyFuel's headquarters in Colorado for the purpose of comprehensive performance and efficiency testing. This testing is complete, and includes the analysis of the collector's optical laser intercept, heat loss of the molten salt-compatible receivers, optical efficiency while tracking the sun, operation with molten salt, and molten salt freeze recovery. Complete results are presented herein for the SkyTrough® DSP parabolic trough.

Peer review by the scientific conference committee of SolarPACES 2014 under responsibility of PSE AG.

Keywords: parabolic; trough; optical; efficiency; molten salt; SkyFuel; SkyTrough; DSP

1. Introduction

SkyFuel has developed, built, and tested a large aperture parabolic trough collector which exhibits both high performance and reduced cost compared to today's leading collectors, and has also demonstrated successful operation of this collector with molten salt as the heat transfer fluid. The measured thermal efficiency of the collector at ambient temperature is 76%, which includes all component and operational factors such as material properties, geometry, and tracking accuracy. This product, the SkyTrough® DSP (Dispatchable Solar Power), is

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fielded at SkyFuel's headquarters in Colorado. From late 2013 through early 2014, DSP trough modules were built and tested to determine both the optical laser intercept and optical efficiency while tracking the sun. Additional testing was completed to establish the heat loss characteristics of 90mm molten salt-compatible receivers, test recovery protocols for molten salt freeze events, and to demonstrate operation of the trough with molten salt.

The SkyTrough® DSP is designed with a 7.6m aperture and 150m total length. These dimensions were determined via an optimization approach [1] that accounted for component and market trends expected for the 2016 timeframe, and included further cost-reducing designs to minimize installed cost. The design, optimization, and testing of the DSP trough was funded in part by DOE grant DE-EE0003584.000.

This document presents the setup, results, and uncertainty analyses for the entire SkyTrough DSP test compendium. Overall results indicated a 76% optical efficiency, and thermal efficiencies ranging from 65% to 75%, conditional to the operating temperature of the heat transfer fluid (HTF).

2. Collector Design

The SkyTrough® DSP is modeled after the SkyTrough®, SkyFuel's 6m aperture, 115m length commercially deployed parabolic trough collector. Both collectors use a lightweight aluminum space frame design to provide the optical substructure and torsional rigidity, precision parabolic ribs to define the optical surface, and ReflecTech polymeric mirror films. A SkyTrough® DSP single module is presented in Fig. 1 at SkyFuel's Colorado headquarters, constructed for the demonstration of optical efficiency and operation with molten salt. An additional module was constructed indoors at SkyFuel's Development and Test Center (DTC) for the purpose of establishing the optical laser intercept.

Fig. 1: Full scale single module (7.6m aperture x 18.5m length) SkyTrough® DSP.

2.1. Cost and Optimization Analysis

The SkyTrough® DSP was designed to provide maximum thermal value (kWh_{th}/$) to a CSP power plant. This optimization, presented in detail in [1], accounted for present and expected future market conditions, material and component prices, and the effects of aperture width, collector length, and receiver selection on trough thermal output. The resulting optimization yielded a 7.6m aperture x 150m length parabolic trough.

2.2. Modeled Collector Performance

Prior to completing the final design and construction of the SkyTrough® DSP, testing was conducted to estimate the achievable contour accuracy as a function of aperture width. This testing predicted a contour accuracy of 2.6mrad (one-σ) for the 7.6m trough. Optical modeling software was then used to extrapolate this contour accuracy into an estimated trough intercept factor and optical efficiency. Ultimately, testing revealed a peak optical efficiency of 76%, more than a percentage point higher than the optical efficiency predicted during the design phase.

3. Component Performance Testing

With the end goal of establishing the thermal efficiency of the SkyTrough® DSP over a range of operating temperatures, SkyFuel executed a number of performance tests. The measurement of optical efficiency while tracking the sun accounted for real-world variables such as tracking accuracy, but was required to be performed at near-ambient temperatures in order to reduce the effects of receiver heat loss. Optical laser intercept testing was performed in order to differentiate the relative contributions of contour and tracking accuracy, while receiver thermal performance testing was performed to ultimately determine the trough's thermal efficiency at any given temperature. The subsections below describe these two tests in detail.

3.1. Laser Intercept Testing

Analytic models were used to estimate the incident angle modifier and end loss factor for the SkyTrough® DSP, but empirical testing was required to determine the contour accuracy of the as-built collector and assess its deviation from an ideal parabolic surface. SkyFuel performed this test indoors on an inverted module, taking over 7,000 data points (approximately 50 data points per square meter of aperture area). The results indicated a 99.1% laser intercept and an average contour accuracy of 2.66 mrad.

For this test the SkyTrough® DSP module was positioned facing the ground, as shown in Fig. 2. Previous internal testing has shown that SkyFuel's tracking position does not have an impact on laser intercept, so an inverted module accurately represents a collector at any elevation. A testing sled was situated below the module on tracks parallel to the module's axis of rotation, with a large diameter target at the focus of the collector. Two-axis scanning of the mirror surface was achieved via self-leveling lasers, which were moved to pre-determined locations across the reflector's surface. In each location, the angular position of the reflected beam on the target was recorded and used to calculate the local contour accuracy. This measurement also provided the laser intercept factor for a given receiver diameter.

Fig. 2: Inverted SkyTrough® DSP module with test sled in position beneath the optical surface.

Nearly 600 data points were recorded for each mirror panel, with 12 panels making up a full module. A sample data set from a single panel is presented in Fig. 3. In this chart, the x-axis represents the position of the laser spot from rim to rim, while the color of the data point indicates the laser spot location along the axial width of the panel. The y-axis shows the local contour accuracy in milliradians (mrad) of each data point taken.

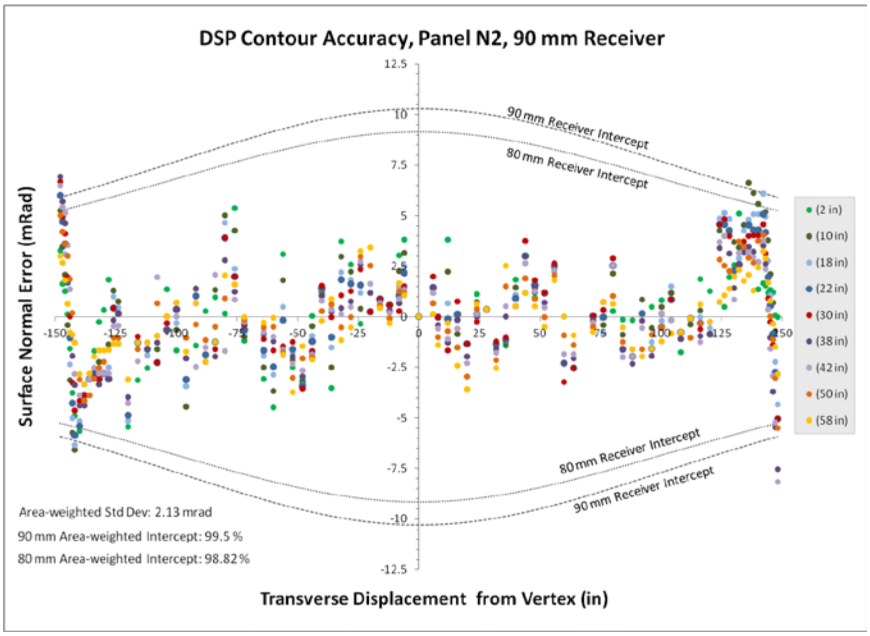

Fig. 3: Contour accuracy and laser intercept testing results for a single SkyTrough® DSP mirror panel.

The curved, dotted lines in the figure indicate the acceptance window for laser intercept given an 80mm or 90mm receiver. The panel presented here demonstrated laser intercepts of 99.5% for a 90mm receiver and 98.8% for an 80mm receiver; the entire trough averaged a 99.1% intercept for 90mm receivers.

3.2. Receiver Thermal Efficiency Testing

Thermal receivers are well insulated from conductive and convective heat losses, but still radiate heat to their surroundings, thereby reducing the overall thermal efficiency of the trough. Since radiative heat loss is a function of temperature to the fourth power, this reduction in thermal efficiency increases rapidly as the operating temperature of the receiver rises. SkyFuel installed prototype receivers in the SkyTrough® DSP test module which were designed for use at elevated temperatures with molten salt. To convert the DSP trough's optical efficiency into a temperature-dependent thermal efficiency, SkyFuel established the receiver's thermal efficiency empirically.

The test stand used for this analysis is presented in Fig. 4. Each end of the receiver was well insulated to mimic field conditions, and an electrical current was run through the receiver to heat the absorber's material resistively. This process is commonly referred to as joule-effect heating. To determine the thermal efficiency of the receiver, it was heated until a steady-state temperature was reached at the wall of the receiver. In a steady-state condition, the power into the receiver is equivalent to the heat loss out, after accounting for estimated receiver end-losses. Input voltage was adjusted to determine heat loss at various temperatures, and the data set yielded a curve for temperature-dependent thermal efficiency.

Fig. 4: Thermal receiver efficiency test stand.

To validate the test stand, SkyFuel first tested a receiver with known heat loss characteristics, which had previously been independently tested for SkyFuel on the National Renewable Energy Laboratory (NREL) Parabolic Trough Receiver Heat Loss Test Stand. Comparison of results from both tests shows that SkyFuel's test stand closely matches receiver heat loss measurements made by NREL.

Figure 5 presents the heat loss curve for the prototype 90mm molten salt receiver as well as the 80mm receiver tested both by SkyFuel and NREL. All three datasets were fit to fourth order polynomials, and included a +/-2.2% total uncertainty (95% confidence interval; see section 4.4).

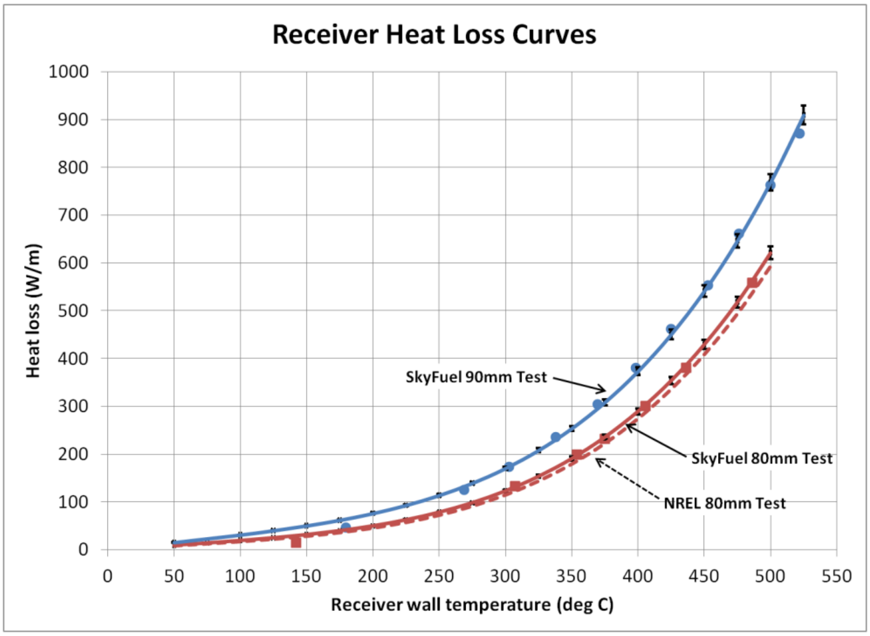

Fig. 5: Heat loss testing results for 80mm and 90mm receivers.

The main contribution to the increased heat loss from the prototype 90mm receiver is its increased surface area over the 80mm receiver.

4. Optical Efficiency Testing

A full-scale SkyTrough® DSP module (Fig. 1) was constructed at SkyFuel's demonstration facility in Colorado and tested to determine the collector's optical efficiency while tracking the sun. To minimize uncertainty due to receiver heat loss, this testing was conducted at near-ambient temperature (~50°C), and results were later combined with the measured receiver heat loss to determine the trough's thermal efficiency at temperatures up to 550°C.

4.1. Test Setup and Instrumentation

The DSP module test facility included the tracking collector along with a fluid loop consisting of flexible hoses to allow trough rotation and receiver expansion, inlet and outlet piping, the HTF pump, heat exchanger, and expansion tank. A 50/50 (volume) mixture of water and ethylene glycol was used as the heat transfer fluid. Inlet and outlet HTF temperatures were measured near to the termination of the receiver string, inside thermowells embedded in the fluid path. These were used in conjunction with thermocouple transmitters and a data acquisition system. Volumetric flow rate of the HTF was measured with a turbine flow meter mounted in the field piping, also relayed via analog transmitter to the data acquisition system.

Fluid temperatures and flow rate were logged every 100ms for the duration of testing. Direct normal irradiance, ambient temperature, and wind speed were measured every second during testing with a rotating shadowband radiometer (RSR) and weather station located approximately 50m from the test module. Periodic measurements taken with a normal incidence pyrheliometer validated the RSR measurements.

This data set, along with the relative sun location and the known relationships of fluid density and specific heat to temperature, provided the required inputs to determine the optical efficiency of the trough.

4.2. Test Procedure and Efficiency Calculation

Testing was conducted over two weeks in May 2014, with preliminary operation used to fine-tune the tracking accuracy to the test site location and collector orientation. Throughout the period of operation, the instantaneous thermal gain (kW) was calculated using Equation 1.

$$\begin{aligned} &\dot{Q}_{\text{gain}} = \dot{m} \cdot C_p \cdot \Delta T - \dot{Q}_{\text{receiverloss}} \\ &\quad \dot{m} = \text{flowrate, kg/s} \\ &\quad C_p = \text{fluid specific heat, kJ/kg°C} \\ &\quad \Delta T = \text{temperature rise, °C} \\ &\quad \dot{Q}_{\text{receiverloss}} \text{ determined empirically as a function of operating temperature} \end{aligned} \tag{1}$$

Input power (kW) was calculated from the direct normal irradiance (DNI, kW/m^2) and adjusted using an incident angle modifier and end loss factor. Both of these adjustments are dependent on the relative position of the sun and the geometry of the trough, with efficiency reported for an equivalency to normal incidence. Equations 2, 3, 4, and 5 present the input power formulas.

$$\dot{Q}_{\text{in}} = DNI \cdot A_{\text{aperture}} \cdot K \cdot EndLoss \tag{2}$$

$$\begin{aligned} &K = IAM \cdot \cos(\theta_d) \\ &\quad \theta_d = \text{incidence angle, rad} \end{aligned} \tag{3}$$

$$IAM = 1 + \frac{0.0278 \cdot \theta_d}{\cos(\theta_d)} - \frac{0.1227\theta_d^{\ 2}}{\cos(\theta_d)} \tag{4}$$

$$EndLoss = 1 - \frac{2 \cdot f \cdot \tan(\theta_d)}{L_{\mathrm{SCA}}} \tag{5}$$

Where f is the collector's focal length, and L_{SCA} is the length of the module. Finally, the instantaneous optical efficiency is given by Equation 6.

$$\eta_{\mathrm{opt}} = \frac{\dot{Q}_{\mathrm{gain}}}{\dot{Q}_{\mathrm{in}}} \tag{6}$$

4.3. Test Results

The optical efficiency of the SkyTrough® DSP was established as 76% +/- 4.8% with a 95% confidence interval. This efficiency is the mean value of a four-hour testing window, which is presented in Fig. 6. Similar results were recorded for other testing days, but this particular dataset yielded the longest period of uninterrupted clear skies.

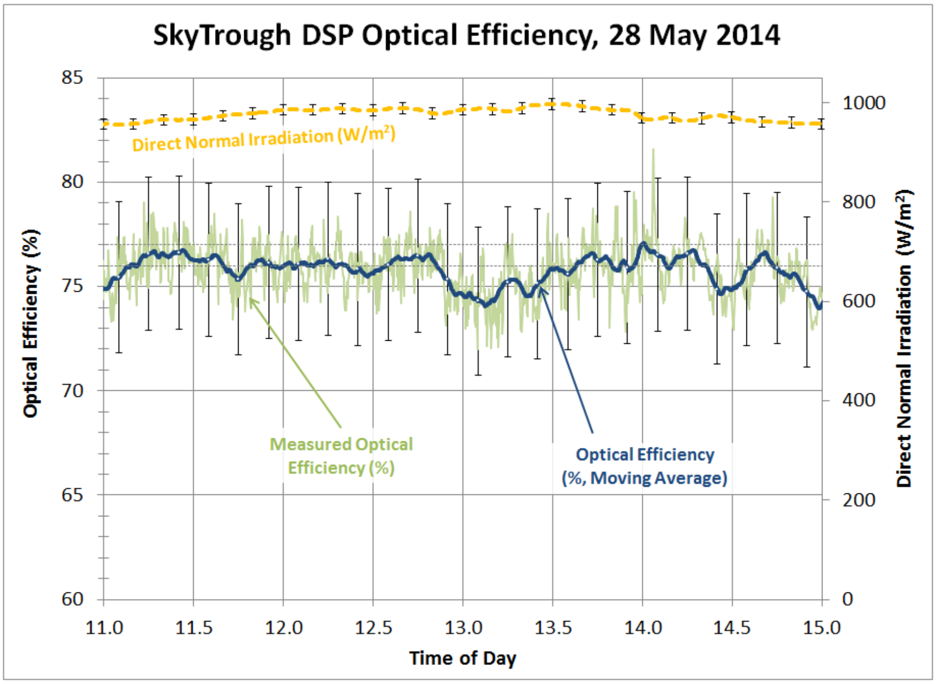

Fig. 6: Optical efficiency test results for the SkyTrough® DSP.

With optical efficiency and heat loss of the thermal receivers, a temperature-dependent thermal efficiency was established. This is presented in Fig. 7, and assumes a DNI of 1,000 W/m^2.

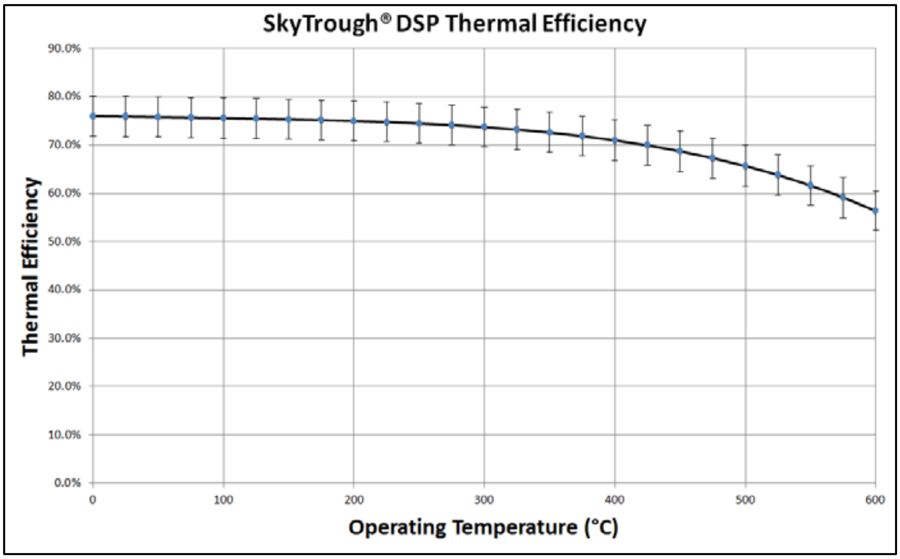

Fig. 7: Thermal efficiency for the SkyTrough® DSP assuming a DNI of 1,000 W/m^2.

Due to the fourth-order nature of radiative heat transfer, the uncertainty of the data increased with temperature. For an oil-based system operating with an inlet temperature of 300°C and an outlet of 400°C, the SkyTrough® DSP thermal efficiency is 72.5% +/- 5.66% (95% confidence). A molten salt field operating with a 300°C inlet and 500°C outlet will yield a thermal efficiency of 70.5% +/- 5.84% (95% confidence). Because collector heat losses climb non-linearly along the length of each loop, these field thermal efficiencies are slightly lower than the single-point efficiency at the average of inlet and outlet temperatures (i.e., 72.6% at 350°C and 71.0% at 400°C). It should also be noted that these thermal efficiencies are indicative of a prototype 90mm receiver; smaller diameter receivers may have lower heat losses and yield a higher efficiency, but will increase parasitic demand and reduce intercept factor. SkyFuel's analysis realized no net economic gain by reducing the receiver diameter.

4.4. Uncertainty Analysis

Measurement uncertainty was defined for each quantitative dataset described above. The classic description of uncertainty (U) is the root sum square (r-s-s) of the uncertainties due to each measured variable, as shown in Equation 7 for the measured power output. The component of uncertainty due to each measured variable is defined as the product of that variable's sensitivity and error.

$$U^2 = \sum_{X_0}^{X_n} \left(\frac{\partial \dot{Q}_{\text{measured}}}{\partial X_i} \cdot \varepsilon_{x_i} \right)^2 \qquad (7)$$

The relationship between each measured variable (e.g., temperature) and the overall test result (e.g., thermal power output) is known (see Equation 1, e.g.), allowing the sensitivity of the test result to be obtained by partial differentiation of the relevant equation.

The error term ε_X defined for each measurement variable combines the measurement's systematic error (the percentage of uncertainty of the instrumentation used to measure the variable) and the random error associated with the variance of the dataset at steady-state. The random error is normalized to the measurement mean, which presents the data in the form of a percent, and is subsequently multiplied by the Student's *t* distribution value to define the data with 95% confidence. The systematic and random errors are combined via the r-s-s method, and the resulting error term is used in Equation 7.

For all temperature measurements, precision type-J thermocouples were used, along with thermocouple transmitters and a data acquisition system. Each piece of equipment included an associated systematic error, which was combined in r-s-s fashion to yield the systematic error of the measurement. All thermocouples were calibrated via a NIST-traceable millivolt source at 17 measurement points over the operating temperature range to reduce the error associated with non-linear thermocouple voltage output. Random error was determined via an analysis of the temperature measurement at steady-state, dividing the standard deviation by the mean and multiplying by the Student's *t* value for the number of measurements analyzed.

Determination of the error present in volumetric flow rate and receiver thermal loss followed a similar procedure. The volumetric flow rate was measured with a turbine flow meter, coupled to a signal converter and a data acquisition system. Voltage, current, and thermocouple measurements for the receiver thermal loss test were recorded directly through a data acquisition system.

Each of these measurement uncertainties is included in Fig. 8. At 95% confidence, the optical efficiency test had a 4.8% total uncertainty, while the thermal loss test had a 2.2% uncertainty.

Measured Value	Sensitivity		Systematic ε	Random σ	Student's *t*	Random ε	Combined ε
T_{in}	5.06	% per %	0.42%	0.337%	1.645	0.554%	3.5%
T_{out}	5.52	% per %	0.42%	0.199%	1.645	0.327%	3.0%
Volumetric Flow	0.99	% per %	0.52%	0.575%	1.645	0.946%	1.1%
Combined Instrument Uncertainty, with a 95% Confidence Level							4.7%

Measured Value	Sensitivity		Systematic ε	Random σ	Student's *t*	Random ε	Combined ε
DNI	1.00	% per %	1.00%	0.183%	1.645	0.301%	1.0%

Total Uncertainty in Optical Efficiency with a 95% Confidence Level	**4.8%**

Measured Value	Sensitivity		Systematic ε	Random σ	Student's *t*	Random ε	Combined ε
Temperature	1.00	% per %	0.41%	0.008%	1.645	0.013%	0.4%
Power	1.00	% per %	0.14%	0.007%	1.645	0.012%	0.1%

Receiver Thermal Loss Measurement Uncertainty	0.4%
Uncertainty in Receiver Thermal Loss Curve Fit	2.2%
Total Uncertainty in Receiver Thermal Loss with a 95% Confidence Level	**2.2%**

Fig. 8: Uncertainty values for SkyTrough DSP tests.

The combination of these two errors, as shown in the thermal efficiency chart (Fig. 7), resulted in a varied uncertainty at different operating temperatures. The sensitivities of the temperature measurement and thermal loss increase with operating temperature, as thermal loss is a function of temperature to the fourth power. As such, the uncertainty of the measurement with a 95% confidence at ambient temperature is 5.4%, while at 550°C it is 6.68%. These variations are included in the figure.

5. Molten Salt Operation

In addition to the efficiency tests described above, SkyFuel also performed operational tests with molten salt as the working fluid. Initial testing consisted of receiver fill, drain, freeze, and thaw tests using the joule-effect heating method, and culminated in full operation and flow through the DSP trough's demonstration loop. Both tests were successful, and did not damage or otherwise alter the equipment.

5.1. Receiver Fill/Drain and Freeze/Thaw Testing

Prior to operation in the full demonstration loop, SkyFuel performed a molten salt operational test on a single receiver under controlled conditions. The receiver was fitted with riser pipes at each end, ensuring a complete fill of the receiver, and allowing excess salt to flow into the receiver as the system cooled and solidified. This system was also attached to a joule-effect heating system, the same test setup that was used for the receiver thermal emittance testing discussed previously.

Testing of this system included four independent trials, each required to confirm safe and maintenance-free operation of the receiver system during operation with molten salt:

i. Preheat the receiver to within 50°C of the salt temperature; fill the receiver with molten salt.
ii. While still hot, drain the receiver of salt.
iii. Allow salt to freeze in the receiver and riser pipes, contracting and filling the receiver completely.
iv. Thaw the frozen salt in the receiver; drain salt from the system.

Each of these tests was completed without damage to the receiver. Elastic deflection of the absorber tube was observed during fill and drain, and was within the range of predicted deflection based on both the weight of the molten salt and the thermal expansion of the absorber due to an uneven circumferential temperature distribution. This deflection was restored to normal conditions once the fill and drain operations were complete and the temperature distribution had settled.

5.2. Demonstration Loop Operation

Once the optical efficiency tests were complete on the SkyTrough® DSP demonstration loop, molten salt was introduced to the system. The entirety of the field piping loop was fitted with electrically resistive heat trace, insulation, and temperature control equipment. Electrical connection lugs were attached at either end of the thermal receiver string, and on either side of the flexible hose equipment to enable heating via the joule-effect method described previously.

Prior to introduction of molten salt into the fluid loop, salt in the storage tank was kept at a temperature of 300°C for a period of seven days to drive off any intermolecular water. The entire field, including the receivers and flexible hoses, was preheated to an average temperature within 50°C of the molten salt to resist thermal shock during the fluid introduction.

Operational tests proved successful with molten nitrate salt, with no damage to equipment, no safety concerns, and successful delivery through the collector loop using the high-temperature pump.

6. Conclusions

The SkyTrough® DSP parabolic trough solar collector assembly studied in this report has demonstrated an optical efficiency of 76% and thermal efficiency of 70.5% while operating with molten salt between 300°C and 500°C. It has also demonstrated successful operation and freeze recovery with molten salt. Due to the promising economics and performance of this collector, SkyFuel intends to continue the path toward commercialization of this product.

References

[1] N. Schuknecht, N. Viljoen, G. Hoste. A novel approach to parabolic trough optimization. Presented at Solar PACES 2013, Las Vegas, NV.