A 14 Year Experimental, Modelling, Reliability and Simulation Study of a Novel Geometry ICPC Solar Collector Demonstration

William S. Duff
Jirachote Daosukho
Colorado State University
Fort Collins CO 80523
bill@engr.colostate.edu

ABSTRACT

A novel geometry ICPC evacuated solar collector was developed at the University of Chicago and Colorado State University in 1993. A 100 m2 array of this collector has been in continuous operation at a demonstration project in Sacramento California since 1998. While operating in the range of 120 to 160C, daily collection efficiencies of nearly 0.50 and instantaneous collection efficiencies of about 0.60 were achieved. Experimental outcomes and collector reliability issues will be presented.

A ray tracing simulation has been designed to investigate the optical performance of this collector. Rays falling on the collector are followed as they are attenuated by various components of the collector until they are absorbed by the fin or escape. Modelled collector properties are ray transmittance and translation, the gap between the glass tube and fin, reflectivity of the reflective surface, absorptivity of the fin and blocking and displacement of the rays by adjacent tubes. Animation of individual rays and associated summary graphics will be shown. Incorporation of the results of the ray tracing into the performance modelling of the collector will be presented.

The novel geometry ICPC collectors were tested on Sandia National Laboratory's two-axis tracking (AZTRAK) platform. Performance of the novel ICPC solar collector at various specified angles along the transverse and longitudinal evacuated tube directions was experimentally measured. To validate the ray tracing simulation, performance predictions are compared to the Sandia results. Data from the initial operation of the Sacramento array are used to further validate the ray tracing simulation.

1. THE NOVEL GEOMETRY ICPC COLLECTOR

1.1 The ICPC Concept

Compound parabolic concentrating (CPC) solar collectors are based on the non-imaging optics principle discovered by Roland Winston almost thirty years ago. Research on this approach has been going on since then. See Garrison [1] and Snail et al [2]. The integral CPC (ICPC) design integrates the geometry of the CPC into an evacuated tube collector, reducing the need for additional support structure.

1.2. The New Design

In 1993 a new family of ICPCs was developed by researchers at the University of Chicago and Colorado State University. One member of this family, shown in Fig. 1, allows a relatively simple manufacturing approach and solves many of the operational problems of previous ICPC designs.

The solar acceptance angle of this design is 180 degrees so that all available diffuse solar radiation is also collected.

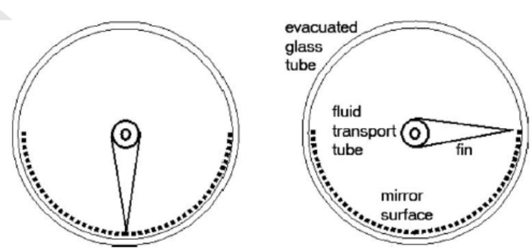

Fig.1. Novel ICPC design showing vertical and horizontal fin orientations

The ICPC uses an absorber fin bonded to a heat transport pipe. The heat transport pipe is housed in an evacuated glass cylinder. The bottom half of the circumference of the glass cylinder is coated with a reflective material. A thin wedge-shaped absorber fin is attached to the heat transport pipe. This ICPC simplifies automated manufacturing and reduces material costs. The "ice-cream cone" shaped absorber configuration decreases the heat loss by a factor of two as compared to the usual flat horizontal fin, which loses heat from both sides of the fin.

1.3. Fabrication

These new ICPC evacuated collector tubes were hand-fabricated from NEG Sun Tube components by a Chicago manufacturer of glass vacuum products. Detailed design and the fabrication approaches for this ICPC are described in Duff et al [3] and Winston et al [4]. As shown in Fig. 1, this ICPC was fabricated with two absorber orientations, one with a vertical absorber fin and one with a horizontal absorber fin..

1.4. Deployment

A non-tracking 100 m^2 336 Novel ICPC evacuated tube solar collector array has been in continuous operation at a solar cooling demonstration project in Sacramento California since 1998. Daily solar collection performance is shown in Fig. 2 and 3.

From 1998 through 2002 the ICPC solar collectors supplied heated pressurized 150^{o}C water to a double effect (2E) absorption chiller which achieved daily COPs of about 1.1. The ICPC collector design operates as efficiently at 2E chiller temperatures (150^{o}C) as do more conventional collectors at much lower temperatures. This new collector made it possible to produce cooling with a 2E chiller with a collector field that is about half the size of that required for a single effect (1E) absorption chiller with the same cooling output.

The daily solar collection efficiencies, based on the total solar energy falling on the collector aperture, at the 140^{o}C to 160^{o}C collector collection requirements of the ICPC evacuated solar collector array is close to 50 percent and instantaneous collection efficiencies of nearly 60. Data collection and analysis has continued from 1998 to the present.

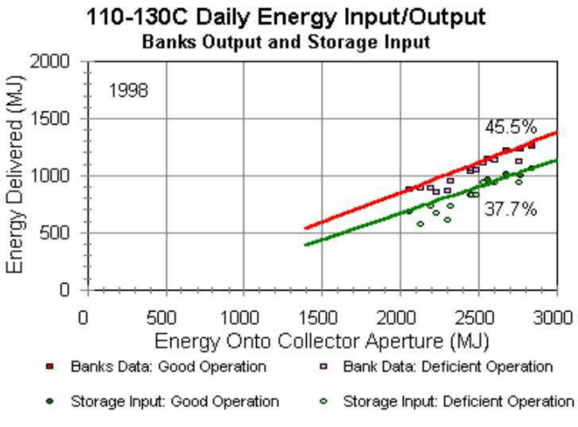

Fig. 2: 1998 Daily Collection Performance for Operation at 110 to 130^{o}C Collector to Ambient Temperature Differences for All Banks and at The Storage. Duff, et.al. [8]

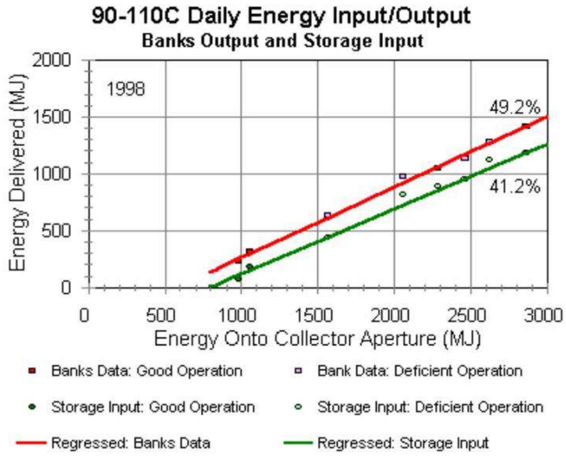

Fig. 3: 1998 Daily Collection Performance for Operation at 90 to 110^{o}C Collector to Ambient Temperature Differences for All Banks and at The Storage. Duff et.al. [8]

2. RAY TRACING ANALYSIS

2.1 Model Development

Fig. 4 and 5 depict the results of an animated graphical ray tracing simulation that has been designed to investigate the optical performance of the ICPC. See, Duff et.al. [10, 11, and 12].

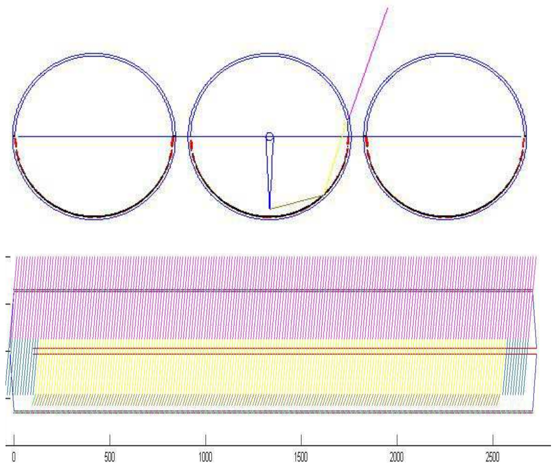

Fig.4. Projected rays on both transverse and longitudinal views on vertical fin ICPC

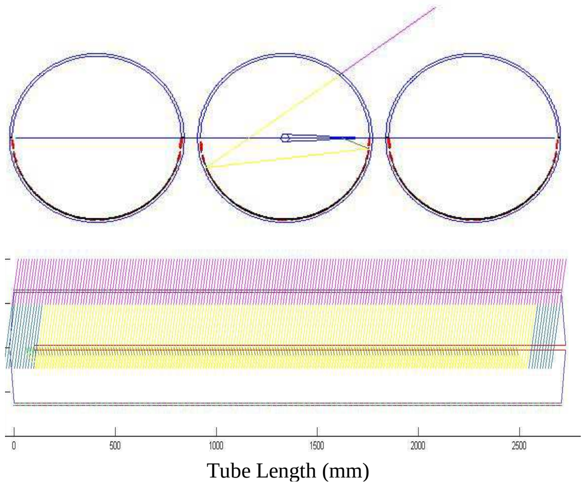

Fig.5. Projected rays for both transverse and longitudinal views for the horizontal fin ICPC

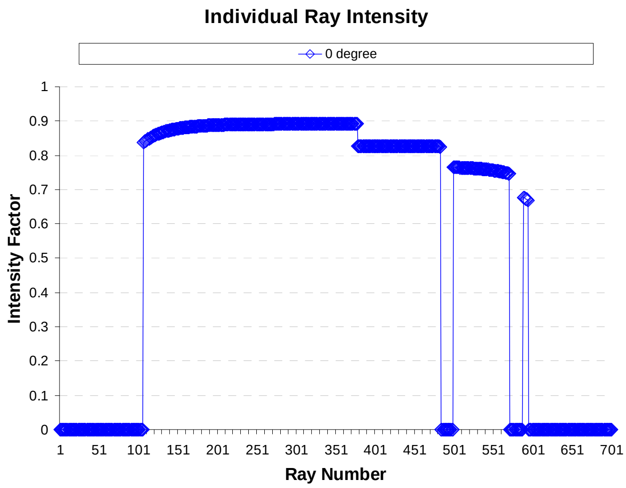

Fig. 6: Horizontal fin intensity factor plots for rays striking at 0 degrees incidence

Factors incorporated into the modeling are the transmittance of the glass tube, the reflectivity of the reflective surface, the gap between the tube surface and the fin and the absorptivity of the fin.

The sun rays are simulated as discrete uniform rays over a range of incident angles from 15 degrees to 165 degrees. The rays are followed through the glass envelope, to the reflector and to the absorber fin. The number of rays absorbed is recorded.

The projected solar radiation is analyzed in the terms of both longitudinal and transverse incident angles to the tube. The reference axis is adjusted to be in the same plane as the collector plane. As shown in the longitudinal view, the simulation follows each ray in the transverse view as a uniformly distributed set of rays. An individual ray traced in the transverse plane is projected to the longitudinal plane as an array of uniformly distributed rays. A ray striking the collector at a given angle and in a given location is monitored as to how it responds at various surfaces and surface orientations of the collector. The degree to which the ray intensity is attenuated at each surface is registered.

2.1 Model Verification

Each cast ray is evenly space over the aperture width. Individual ray intensities are plotted at each angle. For the horizontally oriented fin, at an incident angle of zero degrees (the rays are perpendicular to the collector plane), the first 50 percent of the rays strike the fin directly. Ray intensities are attenuated by the transmittance-absorptivity of the glass cover and the absorptivity of the selective surface of absorber fin. Thus, as seen on figure 6, rays near the horizontal edge of the tube have lower intensities due to a shallow angle of incidence onto the glass cover.

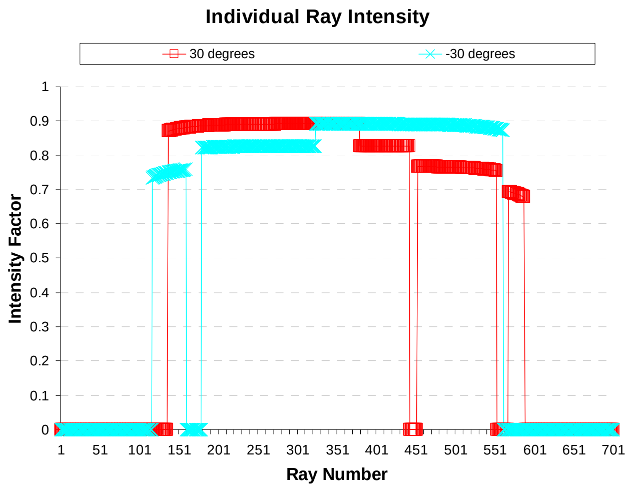

Fig. 7: Comparing horizontal fin intensity factor plots of ray striking analysis between 30 degrees and -30 degree angle of incidence

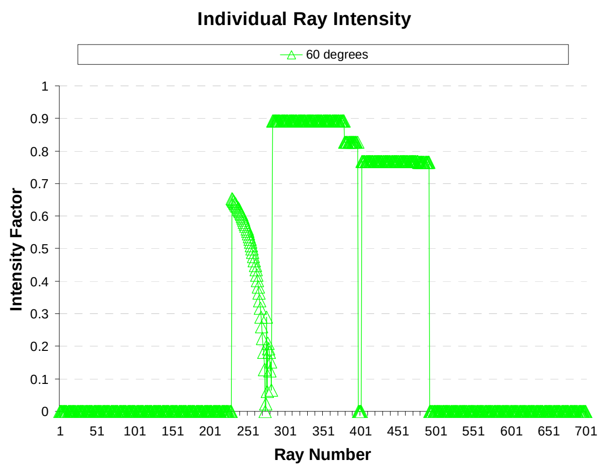

Fig. 8: Intensity factor plots of ray striking analysis at 60 degrees angle of incidence

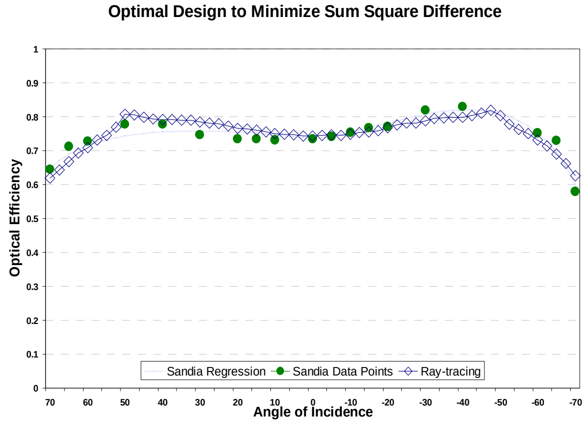

Fig. 9: Optical efficiency plots of ray tracing analysis of the optimum

Later, half of the rays show lower intensity due to hitting the reflector. Some of these rays escape through the gap between fin and the reflector. Multiple hits also show as a further reduction in their intensity. Figure 7 shows a comparison between the rays striking at incidence angles of 30 and -30 degrees (the negative angle represents westward rays). The 30 degree angle of incidence shows more multiple reflector hits than the -30 degree angle of incidence. Figure 8 shows the greater reduction of ray intensity as the ray comes closer to being tangent to the glass cover, eventually reaching zero transmittance due to complete reflection.

2.2 Model Validation

2.2.1 Sandia Tests

To validate the ray-tracing model, the model is configured to recreate the 1998 Sandia experiment. Some, but not all, properties of the actual ICPC tested are reported in Winston et al [5]. For example, the paper did not define the aperture area used in the efficiency calculation. Others values are not precisely known. Thus, in order to match the experimental and the ray-tracing data, feasible component property ranges are estimated and multiple runs are performed varying parameter values within these ranges. Data are also only available in the paper for the horizontal fin orientation. Because incidence angle variations are independently experimentally determined, comparisons will be based on ray racing in the transverse plane of the ICPC. A six-dimensional least squares minimization is performed with values in the range of each factor forming a face-centered central composite design. The ranges are

- Reflectivity of the reflective surface: 0.84 to 0.97
- Gap between the glass and the absorber fin: 1.5 to 8 mm
- Center to center spacing of glass tubes: 135 to 160 mm
- Absorptivity of the fin selective surface: 0.90 to 0.98
- Aperture width: 120 to 125 mm
- Extinction coefficient (K) of the glass: 4 to13 m^{-1}

The sum of squares differences between the efficiencies from experimental data and from ray-tracing process is calculated. Then, the best fit set of design parameter values is selected.

In the least squares analysis, a total of 77 individual runs of ray-tracing analysis were performed and individually analyzed. The best fit set of values is found to be

- Reflectivity of the reflective surface: 0.9270
- Gap between the glass and the absorber fin: 4 mm
- Center to center spacing of glass tubes: 154 mm
- Absorptivity of the fin selective surface: 0.98
- Effective aperture width adjustment: 122 mm
- Extinction coefficient (K) of the glass: 4 m^{-1}

The best fit design run is plotted with the experimental data in figure 9. Note that the center to center spacing between tubes is close to the pitch of 150 mm reported in the Winston et al [5] paper. Moreover, all other values are close to measured and known material property values for the ICPC collector.

2.2.2 Sacramento Demonstration

From direct measurement at the Sacramento installation the gap between tubes is 10 mm, or a pitch 140 mm. Thus, an aperture width adjustment of 140 mm is used for the measured efficiency computations in the Sacramento installation. The difference in the aperture width used in the efficiency computations between the Sandia and Sacramento experiments is quite large. If the ray trace data is normalized by the ratios of the different aperture widths, the Sacramento ray-tracing results match the ray tracing results and measurements for the Sandia experiment. These optical efficiencies are shown in figure 10.

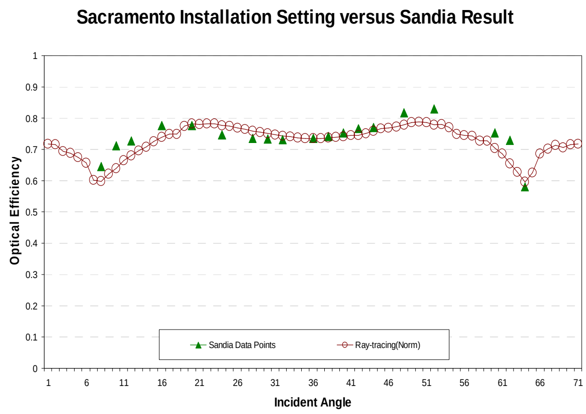

Fig. 10: Optical efficiency plots of ray tracing analysis of the Sacramento installation setting

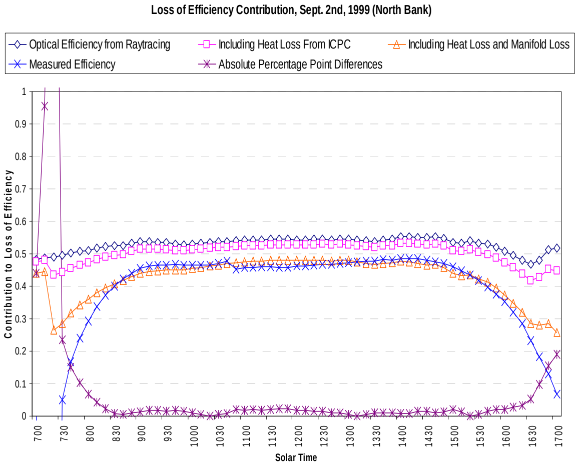

Fig. 11: Comparison between predicted instantaneous efficiency and measured instantaneous efficiency, Sept. 2nd, 1999

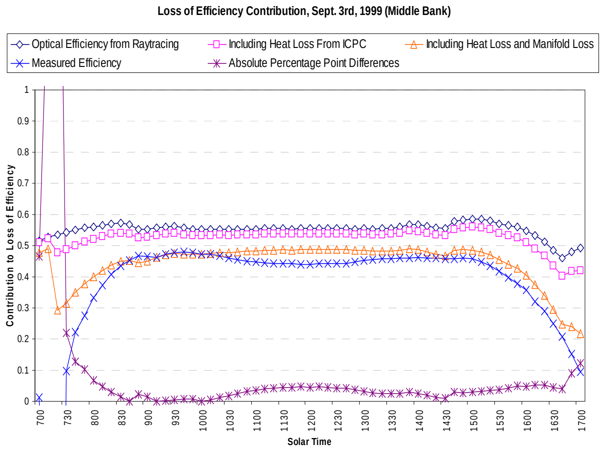

Fig. 12: Comparison between predicted instantaneous efficiency and measured instantaneous efficiency, Sept. 3rd, 1999

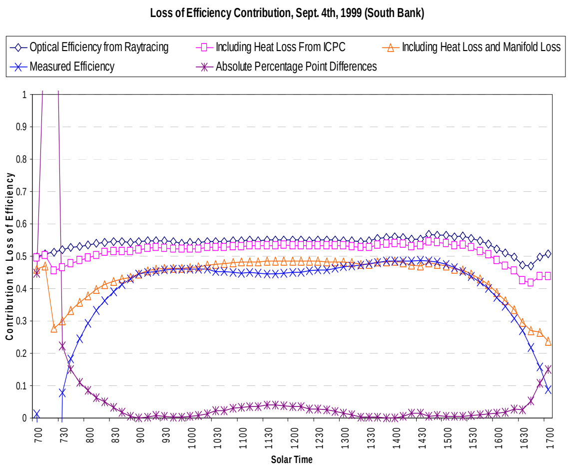

Fig. 13: Comparison between predicted instantaneous efficiency and measured instantaneous efficiency, Sept. 4th, 1999

3. COMPARING ESTIMATED AND MEASURED EFFICIENCIES

3.1 1999 Comparisons

The initial comparisons in September 1999 were made when all the tubes were without any degradation and all instruments were newly calibrated and closely monitored. Each individual bank was investigated and measured. Since all tubes held a complete vacuum, there was no convection loss from the heat transport tube to the glass cover and to the environment.

On September 2, 3, and 4, each of the three banks were run individually. The north bank was tested alone on September 2nd. The measured instantaneous efficiencies are shown by a blue line in Fig. 11. The ray tracing analysis of the North bank horizontal finned ICPC was performed with the insolation data for that day. Then, heat losses estimates for the ICPCs (Fig. 11, magenta line) and manifold were calculated and added to obtain the overall efficiency (Fig. 11, brown line). Comparing overall calculated efficiency (Fig. 9, brown line) with the measured efficiency (Fig. 11, blue line) shows a very good match during 8:30 to 16:30 solar time.

On September 3rd, the middle bank was operated alone. The ray tracing analysis of the vertical finned ICPCs in the middle bank was used to find the array optical efficiency. Fig. 12 shows the same steps of combining the optical efficiencies (dark blue) and thermal efficiencies to reach the overall efficiency (brown). Comparing overall efficiency (Fig. 12, brown line) with the measured efficiency (Fig. 12, blue line), the predicted efficiency shows a close match, though a bit flatter in the middle part of the day, with the measured efficiency displaying a slightly concave appearance in the middle part of the day.

On September 4th, only south bank was operated. The South bank consists of half vertical finned ICPCs and half horizontal finned ICPCs. The ray tracing analyses were performed for the half and half mixture of both fin types. (Fig. 13, dark blue). By including all the thermal losses, the overall efficiency (brown) can be compared to the measured efficiency (blue) in Figure 13. The match is again close. There is a slightly higher percentage point differences (purple) in the middle of the day as compared to differences from 9:00 to 10:30 and 13:30 to 16:00.

All banks are operated on September 8th, a day that was chosen to analyze because the sky was particularly clear. The ray tracing analyses were performed for both fin arrangements. By comparing the predicted overall efficiency to the measured efficiency, the absolute percentage point differences between the two shows less than 10 percent differences. See the purple line in Fig. 1The greatest differences are again in the middle of the day. The average difference from 9:00 to 15:00 is 0.052. Fig. 14 shows the thermal energy plots on this day.

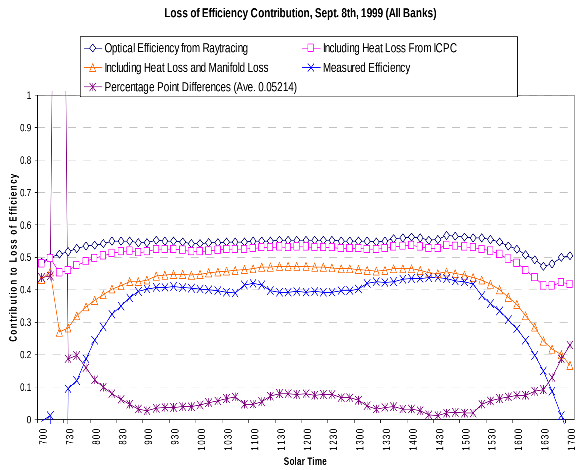

Fig. 14: Comparison between predicted instantaneous efficiency and measured instantaneous efficiency, Sept. 8th, 1999

In all the Figures, a magenta line shows that there is a lesser heat loss from the ICPC tube than from the manifold (the brown line). Collectively, the charts show how the estimated ICPC thermal loss and manifold loss augment the estimated energy from the ray tracing analysis. From the mapped cover temperature, three ICPC heat losses levels are estimated. Overall heat loss is estimated by analyzing individual ICPC tube heat loss tube-by-tube and then adding the estimated manifold heat loss. In all the figures the quantities are plotted against solar time.

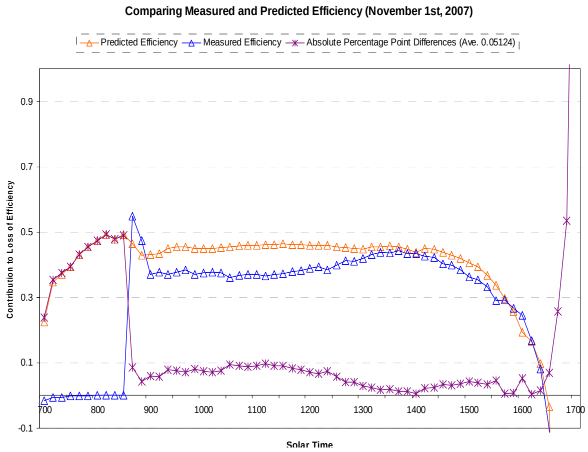

Fig. 15: Comparison between predicted instantaneous efficiency and measured instantaneous efficiency, Nov. 1st, 2007

3.2 2007 Comparisons

In October 2007, all the tubes were inspected and mapped for reflector degradation and cover temperatures. November 1st was chosen due to clear sky and reliable data collecting as compared to other days. The ray tracing analysis is performed for all the tubes in the array. The predicted optical efficiency for each tube as mapped was plugged into the ray tracing routine and then the thermal losses are added to each tube. The predicted overall efficiency was found by averaging all the tube efficiencies.
The measured efficiency showed a late system start. When comparing measured efficiency (blue) and predicted efficiency (brown) (Figure 15), a good match occurs later in the days and there is about 10 percent difference prior to that. The average differences from 9:00 to 15:00 are 0.052 on November 1st.

3.3 Comparing an All Good Tube Scenario Performance in 2007 against Predicted Performance

In order to derive a good estimate of the decrease in array performance due to the two major sources of degradation, loss of vacuum due to cracks and leakage of fluid into the vacuum enclosure, the calculated efficiency using all good tubes and the 2007 calculated efficiency with degraded tube is plotted in figure 16. This figure shows that there is about a 5 percent differences. Since the 1998/99 and 2007 measured versus predicted differences are nearly the same, degradation in performance could reasonably be assumed to be wholly attributable to these two sources.

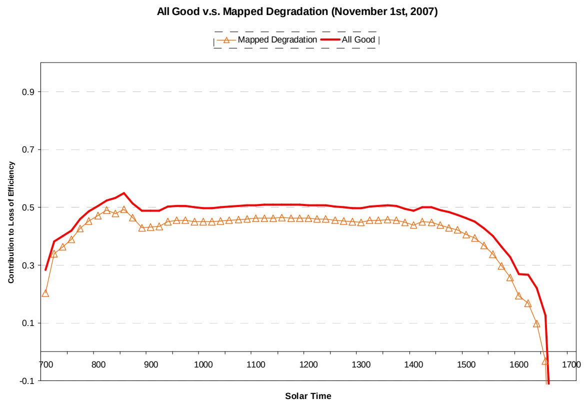

Fig. 16: Comparison between all good tube and mapped degradation efficiency, Nov. 1st, 2007

4. CONCLUSIONS

A detailed ray tracing analysis for characterizing the optical performance of the novel ICPC evacuated tube collector has been described and its results have been illustrated.

A verification of the ray tracing approach is virtually presented in the traced ray graphics. See figure 6, 7, and 8.

By matching ray tracing results with experimental data, the validation of the ray tracing model has been accomplished.

Heat loss from both the ICPC tubes and the manifold plays an important role in overall performance.

Overall performance is also degraded by the loss of vacuum in the tube and leakage of fluid into the vacuum enclosure. An analysis of the performance consequences of reflector degradation due to fluid leakage and loss of vacuum has been compared with measured data. The predicted efficiency matches well with the measured efficiency, especially during at the beginning and the end of the day. The average differences in efficiency are quite close for the time interval from 9:00 to 15:00 in both 1999 and 2007. Thus the predicted extent of the decrease in efficiency from an all good tube situation and the 2007 level of degradation appear to substantiate the dominating importance of the two identified degradation mechanisms.

5. REFERENCES

(1) Garrison, J. D., Optimization of Fixed Solar Thermal Collectors, **Solar Energy**, v23, 1979

(2) Snail, J. J., O'Gallagher and R. Winston, A Stationary Evacuated Collector with Integrated Concentrator, Solar Energy, v33, 1983

(3) Duff, William S, R. Duquette, Roland Winston and Joseph O'Gallagher, Development, Fabrication and Testing of a New Design for the Integrated Parabolic Evacuated Collector, Proceedings of the ASES/ASME Solar Energy Forum, Washington D. C. April, 1997

(4) Winston, R, J. J. O'Gallagher, William S. Duff and Alberto Cavallaro, The Integrated Compound Parabolic Concentrator: From Development to Demonstration, Proceedings of the ASES/ASME Solar Energy Forum, Washington D. C., April, 1997.

(5) Winston, R, O'Gallagher, J., Mahoney, A. R., Dudley, V. E. and Hoffman, R., "Initial Performance Measurements from a Low Concentration Version of an Integrated Compound Parabolic Concentrator (ICPC)", Proceedings of the 1998 ASES Annual Conference, Albuquerque NM, June, 1998

(6) Winston, Roland, W. Duff, J. O'Gallagher, T. Henkel, R. Christiansen and J. Bergquam, "Demonstration of A New Type of ICPC in a Double-Effect Absorption Cooling System", International Solar Energy Society Congress, Jerusalem, Israel, July 1999.

(7) Duff, W. S., Winston, R., O'Gallagher, J., Henkel T. and Bergquam, J., "Five Year Novel ICPC Solar Collector Performance", 2003 American Solar Energy Society Solar Energy Conference, Austin TX, June 2003

(8) Duff, William, Roland Winston, Joseph O'Gallagher, Tom Henkel and Jim Bergquam, "Performance of the Sacramento Demonstration ICPC Collector and Double Effect Chiller in 2000 and 2001", **Solar Energy**, v76, pages 175-180, January 2004.

(9) Duff, William, Jirachote Daosukho, Klaus Vanoli, Roland Winston, Joseph O'Gallagher, Tom Henkel and Jim Bergquam, "Comparisons of the Performance of Three Different Types of Evacuated Tubular Solar Collectors", American Solar Energy Society 2006 Congress, Denver, Colorado, July 2006.

(10) Duff, William S. and Jirachote Daosukho, "A Performance and Reliability Study of a Novel ICPC Solar Collector Installation", American Solar Energy Society 2007 Congress, Cleveland, Ohio, July 2007.

(11) Duff, William S. and Jirachote Daosukho, "Eleven Year Evaluation of a Novel ICPC Solar Collector Installation: The Role of Failure Modes in Changing Optical and Thermal Performance", American Solar Energy Society 2008 Congress, Buffalo NY, May 2009.

(12) Duff, William S, Jirachote Daosukho and Bengt Perers, "Three Dimensional Ray Tracing and Reliability Analyses of a Novel ICPC Collector after Twelve Years Of Operation", 2010 SWC Eurosun Congress, Graz, Switzerland, September 27-29, 2010.