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Experimental Validation and Model Verification for a Novel Geometry ICPC Solar Collector

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Abstract

A novel geometry ICPC solar collector was developed at the University of Chicago and Colorado State University. A ray tracing model has been designed to investigate the optical performance of both the horizontal and vertical fin versions of this collector. Solar radiation is modeled as discrete uniform rays. 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. The extent to which each absorbed ray is attenuated is recorded. Modelled collector properties are transmittance and translation of a ray passing through transparent media, the size of 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. .

Presentation of the progressive animation of individual rays and associated summary graphics at the various specified incident angles provide model verification for the investigation into causes of ray attenuation and provide accounts for rays that escape.

Two fourteen tube modules were tested on Sandia National Laboratory's two-axis tracking (AZTRAK) platform. By adjusting the tracking of the platform to the desired incident angle of the sun's rays, performance of the novel ICPC solar collector at various specified angles along the transverse and longitudinal evacuated tube directions were experimentally determined. To validate the ray tracing model, transverse and longitudinal performance predictions at the corresponding specified incident angles are compared to the Sandia results.

A 100 m2 336 Novel ICPC evacuated tube solar collector array has been in continuous operation at a demonstration project in Sacramento California since 1998. Data from the initial operation of the array are used to further validate the ray tracing model.

Examples of the progressive casting of individual rays across the evacuated tube aperture width and the fit to experimental data are shown in the accompanying figures.

1. The Novel Geometry ICPC Collector

1.1. ICPC Concept

Research on CPC solar collectors has been going on for almost thirty years. See Garrison [1] and Snail et al [2]. In the early 1990s a new ICPC evacuated collector design was developed. The new ICPC design allows a relatively simple manufacturing approach and solves many of the operational problems of previous ICPC designs. The design and the fabrication approaches are described in Duff et al [3] and Winston et al [4].

1.2. The New Design

An integral compound parabolic concentrating collector, or ICPC, integrates the geometry of the CPC into an evacuated tube collector, eliminating the need of an additional structure. The ICPC uses an absorber fin bonded to a heat transport pipe. The heat transport pipe is housed in the 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. The ICPC simplifies automated manufacturing and reduces material costs. An “ice-cream cone” shaped absorber configuration provides more effective concentration compared to the usual flat horizontal fin absorber evacuated tube configuration, which loses heat from both sides of the fin. See Duff et al [3].

1.3. Development and Fabrication

The evacuated collector tubes are based on a novel ICPC design that was developed by researchers at the University of Chicago and Colorado State University in 1993. The evacuated collector tubes were hand-fabricated from NEG Sun Tube components by a Chicago area manufacturer of glass vacuum products. The new ICPC evacuated tubes were fabricated with two absorber orientations, one with a vertical absorber fin and one with a horizontal fin. A cross-section of the collector tube illustrating the two orientations is shown in Figure 1.

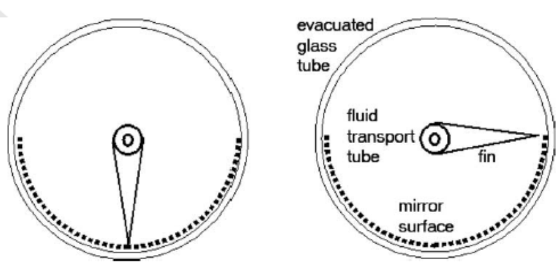

Fig.1. Novel ICPC design showing vertical and horizontal fin orientations

1.4. Deployment

A 100 m^2 336 Novel ICPC evacuated tube solar collector array has been in continuous operation at a demonstration project in Sacramento California since 1998. From 1998 through 2002 demonstration project ICPC solar collectors supplied heated pressurized 150C water to a double effect (2E) absorption chiller. The ICPC collector design operates as efficiently at 2E chiller temperatures (150C) as do more conventional collectors at much lower temperatures. This new collector made it possible to produce cooling with a 2E chiller using a collector field that is about half the size of that required for a single effect (1E) absorption chiller with the same cooling output. Data collection and analysis has continued to the present [6 through 12].

2. Ray tracing Analysis

2.1. Model Development

Fig. 2 and 3 depict the results of an animated graphical ray tracing simulation that has been designed to investigate the optical performance of the ICPC [10 through 12]. Factors incorporated 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.

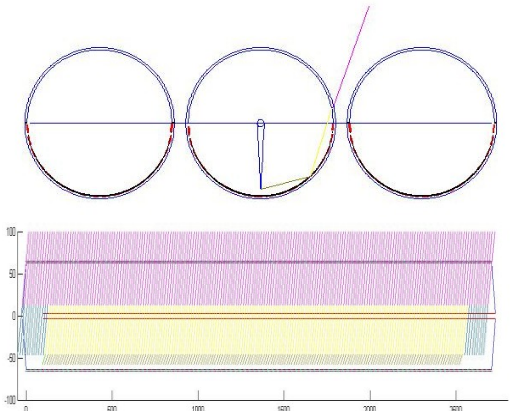

Fig.2. Projected rays on both transverse and longitudinal views on vertical fin ICPC

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. A ray striking the collector at a given angle and in given location is monitored as to how it responds at various surfaces and orientations of the collector. The degree to which the ray intensity is attenuated at each surface is registered. A color code shown in Table 1 provides a means of following how simulated rays respond at the various surfaces. An individual ray traced in the transverse plane is projected to the longitudinal plane as an array of uniformly distributed rays. The ray tracing procedure is set up to trace individual rays and their intensities until one hits the absorber plate or is reflected out. The direction of the ray travelling in the ICPC tube is recorded and projected into both transverse and longitudinal views.

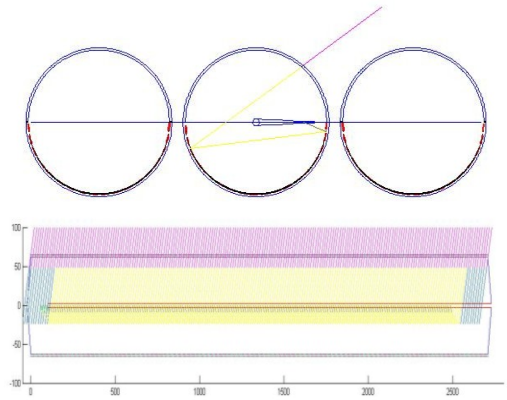

Fig.3. Projected rays for both transverse and longitudinal views for the horizontal fin ICPC

Table 1. Color codes to illustrate ray action

Color	Code
Pink	Ray enters outer glass tube
Red	Ray hits heat transport tube
Blue	Ray missing aperture area
Yellow	Ray hits reflective surface
Brown	Ray hits absorber fin
Green	Ray is reflected out

As each ray is cast on the transverse plane, a uniform distribution of rays throughout the longitudinal view is also analyzed. Each ray is followed starting from where it enters the tube. The pink color code will mark the ray from outside of the glass cover to the point of its entrance. After a ray (pink colored) enter the glass tube, the ray is examined to see if it hits or misses the reflector. The rays that miss the reflector or absorber are then colored blue. The remaining rays then hit the reflector, perhaps multiple times, before hitting the absorber or being reflected out of the glass tube.

The reflected angle in the longitudinal view is calculated by using its recorded last reflected position from the transverse view and this is then applied to the longitudinal view. At this point each reflected ray is color coded yellow. After this reflection, each ray is followed and investigated to see if it hits the absorber (brown) or is reflected out (green).

2.2 Model Verification

Individual ray intensities are plotted at each angle to verify the ray tracing process. For the horizontally oriented fin, at an incident angle of zero degrees, 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 4, rays near the edge of the glass cover have lower intensities due to a shallow incident angle of incidence onto the glass cover. Later, half of rays show lower intensity due to hitting the reflector. Some rays, showing zero intensity, escape through the gap between fin and the reflector. Multiple hits also show as a further reduction in their intensity. Figure 5 shows a comparison between rays striking at incidence angles of 30 degrees and -30 degrees. The 30 degree angle of incidence shows more multiple reflector hits than the -30 degree angle of incidence.

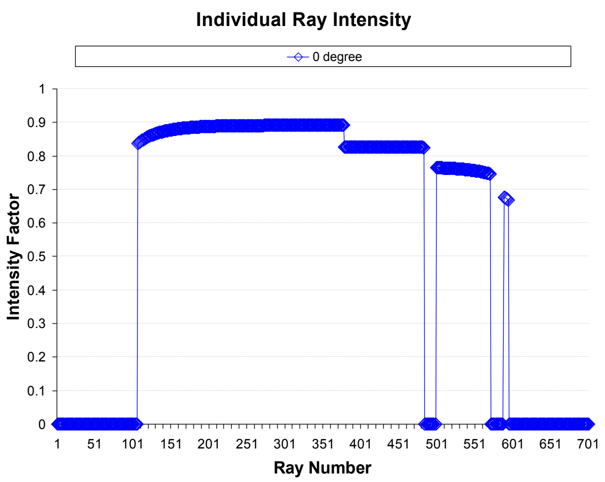

Fig. 4: Horizontal fin intensity factor plots for rays striking at 0 degrees incidence

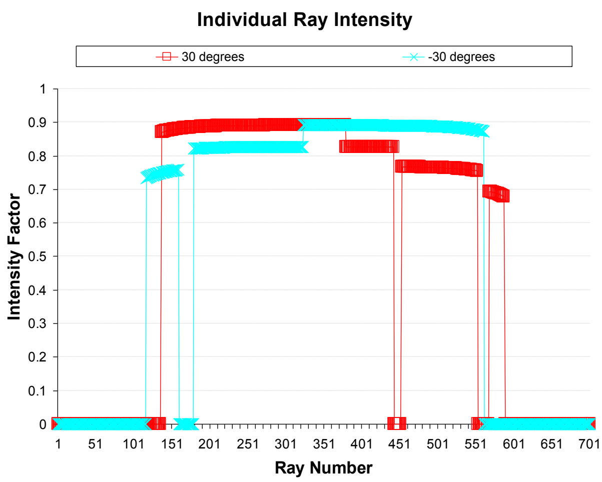

Fig.5: Comparing horizontal fin intensity factor plots of ray striking analysis between 30 degrees and -30 degree angle of incidence

Figures 6 and 8 show how rays are attenuated by passing through the glass cover of the adjacent tube. Figure 7 and 9 show 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. At a 60 degree angle of incidence there are more multiple reflector hits than at -60 degrees, resulting in a lower total optical efficiency.

2.3 Model Validation

2.3.1 Sandia Tests

To validate the ray-tracing model, the model is configured to recreate the 1998 Sandia experiment.

Some properties of the actual ICPC tested are not reported in Winston et al [5]. For example, the paper did not define the aperture area used in the efficiency calculation. Also, some others 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. Also, data are only available in the paper for the horizontal fin arrangement. 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

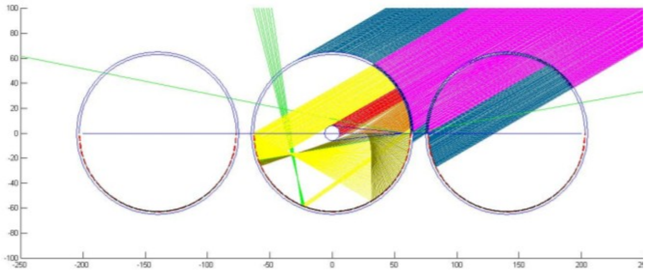

Fig. 6: Ray tracing analysis at 60 degrees angle of incidence

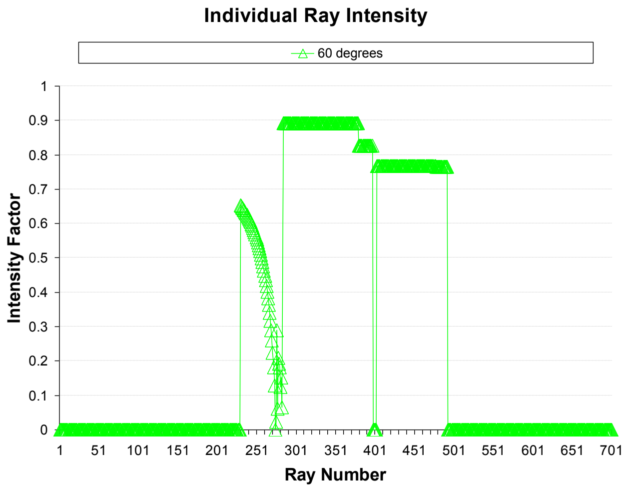

Fig. 7: Intensity factor plots of ray striking analysis at 60 degrees angle of incidence

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

The effective aperture width is a variation in the width dimension of the aperture area used in the efficiency calculation. It appears that the aperture width used in the paper is based on the tube and/or fin width and did not incorporate the gaps between the tubes. A pitch of 150 mm is stated in the Winston et al paper [5]. The pitch range from 135 to 160 mm is chosen to provide a wide range that includes the 140 mm pitch of the Sacramento demonstration. The fin gap range from 1.5 to 8 mm will accommodate possible fin distortion and positional variability. The ranges of the reflectivity and the absorptivity encompass the measured reflectivity of 0.934 and measured absorptivity of 0.95 in Duff et al [11]. The range of the extinction coefficient of the glass-cover from 4 to 13 m^{-1} corresponds to a wide range of glass quality from "water white" glass to poor glass.

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

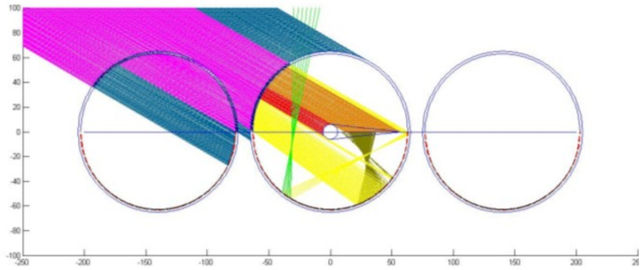

Fig. 8: Ray tracing analysis at -60 degrees angle of incidence

In the least squares analysis, a total of 77 individual runs of ray-tracing analysis were performed and individually analyzed. Figure 10 depicts an example comparison of ray tracing data and experimental data. Results of all 77 runs are recorded and analyzed. The best fit set of values is found to be

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

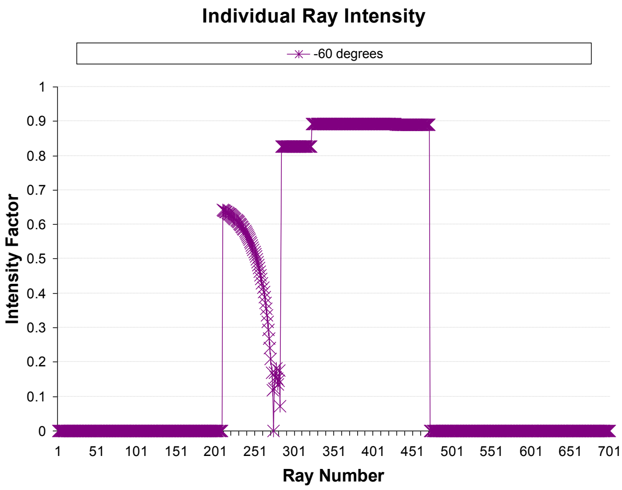

Fig. 9: Intensity factor plots of ray striking analysis at -60 degrees angle of incidence

A ray tracing confirmation run of the best fit design is then performed. The result of this run is plotted with the experimental data and their ranges in figure 11. Notice 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.

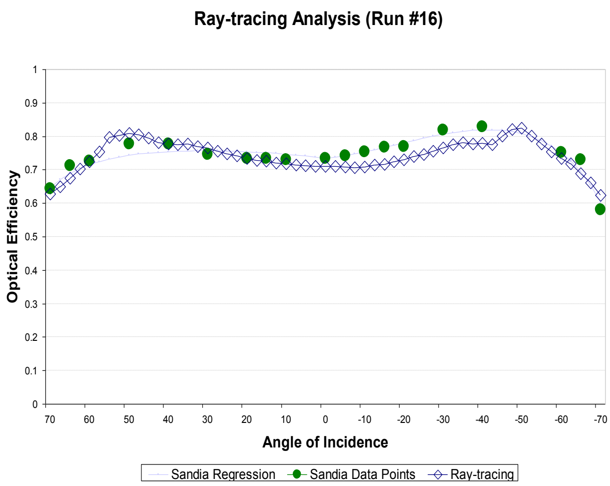

Fig. 10: Optical efficiency plots of ray-tracing analysis (Run #16)

2.3.2 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. These values are shown in table 2. 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 12.

Table 2: Sacramento installation parameter values

Pitch	Gap	Absorptivity	Reflectivity	Effective aperture width adjustment	K	Y=SSD (Norm)	Y=SSD
140	6.0	0.947	0.9348	140/122	4	0.0266	0.3053

3. Conclusions

A detailed ray tracing analysis for characterizing the optical performance of the novel ICPC evacuated tube collector has been described and its results illustrated. Verification of the ray tracing is presented by means of traced ray graphics. By matching ray tracing results with experimental data, the validation of the ray tracing model has been accomplished.

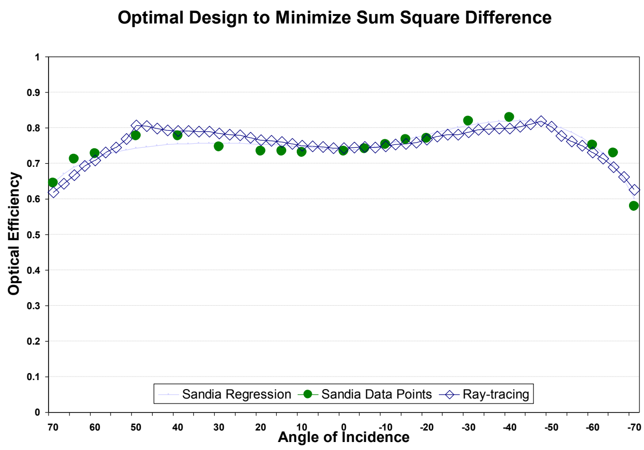

Fig. 11: Optical efficiency plots of ray tracing analysis of the optimum design

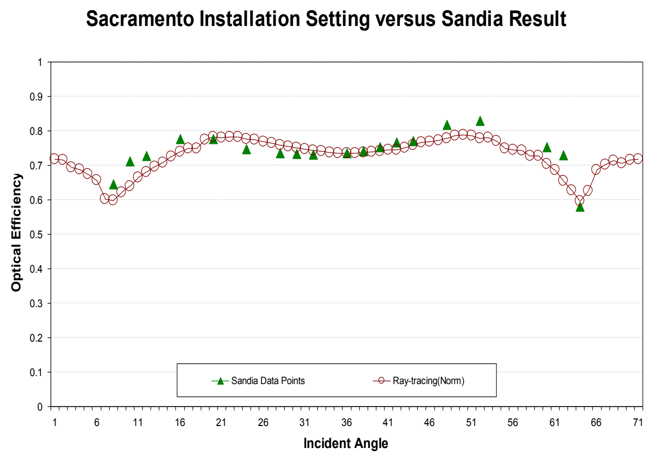

Fig. 12: Optical efficiency plots of ray tracing analysis of the Sacramento installation setting

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