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Twenty Years’ Experience with a Novel Geometry ICPC Evacuated Solar Collector

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Abstract

A novel geometry ICPC evacuated tube solar collector was developed at the University of Chicago and Colorado State University in 1993. Individual evacuated tubes of this novel geometry ICPC were experimentally fabricated and tested at Colorado State University in 1994-96 and at the University of Chicago in 1996-97. In 1998 two 14 tube modules were tested on Sandia National Laboratory’s two-axis tracking (AZTRAK) platform in Albuquerque New Mexico by Sandia National Laboratory and the University of Chicago. A 336 tube 100 m2 array of this collector has been in continuous operation at a demonstration project in Sacramento California since 1998. From 1998 to the present performance of the Sacramento demonstration array and single and double effect cooling systems has been monitored and evaluated by the California State University at Sacramento and Colorado State University. Optical ray tracing modelling, thermal performance modelling and collector reliability studies have been conducted by Colorado State University during the 1998 to 2013 period. Performance approaching the theoretical predictions was achieved for the individual ICPC evacuated tubes experimentally fabricated by Colorado State University and the University of Chicago. While operating in the range of 120 to 160C, daily solar collection efficiencies of nearly 0.50 and instantaneous solar collection efficiencies of about 0.60 were achieved. Daily cooling COPs of 1.1 were achieved while operating the double effect chiller with energy supplied from the ICPC solar collectors. A ray tracing simulation incorporating 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 has been developed. Animation of individual rays and associated summary graphics and an optical and thermal performance model of the collector have also been developed. Performance of the novel ICPC solar collector at various specified angles along the transverse and longitudinal evacuated tube directions was experimentally measured on the Sandia National Laboratory’s two-axis tracking (AZTRAK) platform. Data from the Sandia tests was used to validate the ray tracing simulation performance. Data from the initial operation of the Sacramento array were used to further validate the ray tracing simulation and thermal modelling. The primacy of the two identified collector reliability failure modes was established. Details of the various testing and research activities and results are presented. Animations of the ray tracing are also included in the oral presentation.

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1. Background and Methods

1.1. Background

Flat plate solar collectors are popular for low cost solar energy collection. Their low efficiency and low operating temperature limitations restrict their practical uses to heating domestic hot water and warming swimming pools. At comparable costs, evacuated collectors and compound parabolic concentrators (CPC) provide higher efficiencies and better performance at higher temperatures and lower levels of solar radiation. Thus, solar thermal collector applications can be broadened to include air conditioning and industrial uses as well as cost effective operation in poorer solar radiation locations.

Research on integral compound parabolic concentrator (ICPC) evacuated solar collectors has been going on for more than thirty years Garrison [1] and Snail et al [2]. In the early 1990s a family of designs for a new unique integral compound parabolic concentrator (ICPC) was developed by researchers at the University of Chicago and Colorado State University. The new ICPC integrates the geometry of the CPC reflector into an evacuated tube collector. The new ICPC design allows a relatively simple manufacturing approach and solves many of the operational problems of previous ICPC designs. This design and the fabrication approaches are described in Duff et al [3] and Winston et al [4].

1.2. The New Design

The version of the new ICPC tested has the potential for especially low manufacturing costs. The evacuated tube itself eliminates the need and cost of much of the support structure required in a flat plate collector. The new ICPC’s absorber consists of a selectively coated fin bonded to a heat transport pipe. (See Fig. 1.) This assembly 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 absorber fin is folded over into a wedge shape. The “ice-cream cone” shaped absorber configuration provides twice the effective concentration compared to the usual flat horizontal fin absorber evacuated tube configuration, which loses heat from both sides of the fin. The solar acceptance angle of this design is 180 degrees so that all available diffuse solar radiation is also collected. In a series of experiments in 1999, the two differently oriented finned collectors were found to yield essentially identical performance.

![Fig. 1. Novel ICPC design showing vertical and horizontal fin orientations](image-url)
1.3. Development and Fabrication

The evacuated collector tubes tested at Sandia and incorporated into the Sacramento demonstration 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 absorber fin. A cross-section of the collector tube illustrating the two orientations is shown in Figure 1.

1.4. Testing

Before the novel ICPC was installed at the Sacramento demonstration, seven ICPC modules of each absorber fin orientation were tested on the Sandia National Laboratory’s two-axis tracking (AZTRAK) platform in Albuquerque New Mexico by Sandia National Laboratory and the University of Chicago, Winston et al, [4]. This platform allows a non-tracking solar collector to be positioned at any angle between zero and 90 degrees in any orientation. Early instantaneous efficiency estimation models were formulated using regression analysis from these experiments.

1.5. Deployment

1998 to the present, a 100 m² 336 tube array of the novel ICPC evacuated tube solar collectors has been in continuous operation at a demonstration project in Sacramento California. From 1998 through 2002 the ICPC solar collectors supplied heated pressurized 150°C water to a double effect (2E) absorption chiller. The ICPC collector design operates as efficiently at 2E chiller temperatures (150°C) 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.
2. Results

Performance approaching the theoretical predictions was achieved for the individual ICPC evacuated tubes experimentally fabricated by Colorado State University and the University of Chicago.

2.1. Development and Fabrication

Daily solar collection efficiencies of the non-tracking ICPC evacuated solar collector array in the Sacramento Demonstration are close to the 50 percent and instantaneous collection efficiencies close to 60 percent while operating at the 140°C to 160°C temperatures required by the demonstration’s 2E absorption chiller. (These efficiencies are based on a total collector aperture area which included the gaps between the glass tubes.) These high daily efficiencies seen throughout much of 1998-99 were achieved while the collector array operation was not optimally controlled. Despite this, the non-tracking ICPC evacuated solar collector array provided daily solar collection efficiencies close to theoretical. Also, during this period, daily cooling COPs of 1.1 were achieved while operating the 2E chiller with energy supplied from the ICPC solar collectors.

2.2. Degradation and Failure

Degradation and failure mechanisms for the 20 years of operation of the novel ICPC array in Sacramento were investigated. The two main degradation mechanisms are air leakage through cracks in the glass enclosures and and fluid leakage into the vacuum enclosure from the heat transport tubes. Both cause a reduction in optical and thermal performance. Air leakage causes a gradual degradation of the reflective surface, whereas fluid leakage results in a much more rapid degradation. Molecules of air or of the fluid introduce convection and conduction losses. Under substantial degradation of the reflector, the horizontal fin ICPC retains better optical performance than the vertical fin ICPC. All of the 336 evacuated tubes’ reflectivities and glass cover temperatures were mapped. Ray tracing analysis and heat loss analysis were performed for each tube and the resultant degraded array efficiency was predicted. In
comparing predicted array efficiency and measured array efficiency, the two show close agreement, especially near the end of the day. The average differences between measured and predicted efficiencies levels are about 5% in the time interval 9:00 to 15:00 from 1999 to 2007.

2.3. Ray tracing Analysis

2.3.1. 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, Duff et.al. [10, 11, and 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 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 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. An individual ray traced in the transverse plane is projected to the longitudinal plane as an array of uniformly distributed rays.

2.3.2. Model Verification

Each ray is casted evenly space over the departure width. 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 (when 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. 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 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.

2.3.3. Model Validation

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

- 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 to 13 m⁻¹

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. In the least squares analysis, a total of 77 individual runs of ray-tracing analysis were performed and individually analyzed. 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

Fig. 8: Optical efficiency plots of ray tracing analysis of the optimum design

Fig. 9: Optical efficiency plots of ray tracing analysis of the Sacramento installation setting
• 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\(^{-1}\)

2.3.4. 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 9.

2.4. Comparing estimated and measured efficiencies

2.4.1. 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 Figure 10. 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 (Figure 10, magenta line) and manifold were calculated and added to obtain the overall efficiency (Figure 10, brown line). Comparing overall calculated efficiency (Figure 9, brown line)
with the measured efficiency (Figure 10, 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. Figure 11 shows the same steps of combining the optical efficiencies (dark blue) and thermal efficiencies to reach the overall efficiency (brown). Comparing overall efficiency (Figure 11, brown line) with the measured efficiency (Figure 11, blue line), the predicted efficiency (brown) shows a close match, 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 a half and half mixture of both fins. By including all the thermal losses, the overall efficiency can be compared to the measured efficiency. The match is again close. There is a slightly higher percentage point differences 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 a less than 10 percent differences. The greatest differences are again in the middle of the day. The average difference from 9:00 to 15:00 is 0.052.

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.
2.4.2. 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 12), 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.

2.4.3. 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 15. 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.

3. Conclusions

The ray tracing analysis provides an understanding of the optical performance and detailed optical efficiencies of the novel ICPC at various incident angles. The detailed ray tracing shows how each ray’s intensity is attenuated. The animated graphical ray tracing allows the user to visualize the propagation of rays through the ICPC optics. Using the ray tracing analysis the optical efficiencies during daytime operating hours for both vertical and horizontal fin orientations of the ICPC have been investigated. It was found that a horizontal fin ICPC has a slightly better optical performance than a vertical fin ICPC. The ray tracing analysis also showed that the horizontal fin ICPC’s performance was more robust to degradation of the reflective surface. The ray tracing analysis also provides a two-dimensional incident angle modifier formulation that is superior to earlier IAM characterizations. 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.

References


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