Industrial Steam Generation by Non-Imaging Focusing Final Report February, 1979

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1. Introduction

An innovative solar collector for industrial steam generation has been designed, developed, and built by CEER with cooperation and funding from the University of Chicago and Bacardi Corporation. The collector is a linearly segmented compound parabolic concentrator (CPC) with a cylindrical evacuated tube as the receiver. As part of the project, a solar radiation measuring station was installed on the premises of the Bacardi Rum Distillation Plant in Cataño, Puerto Rico. This report emphasizes the portion of the project carried out after the First Progress Report of August, 1978. We refer the reader to that report for details of the initial phases of the project. In general, that report dealt with the general design ideas and the preliminary analytical studies of these ideas. Some work with an experimental model was also included. This report covers mainly the final design and construction of the collector. The main design elements that are incorporated in this collector are now summarized. First, it is a CPC collector with a concentration ratio of 5.25. This means it can make use of diffuse as well as direct sunlight. This also means it does not require continuous or even daily tracking of the sun's

Position. Second, it features an evacuated tubular receiver of a new design. This receiver is expected to outperform other receivers made for high-temperature collectors. Third, the compound parabolic concentrator (CPC) mirror surface is segmented and encapsulated in glass tubes. These tubes offer lightweight, low-cost structural support, and protection for the mirror surface.

11. Design and Fabrication of Collector Components

The major system components of the linearly segmented compound parabolic collector under consideration are depicted in schematic form in Figures 1, 2, and 3. These illustrate the evacuated tubular receiver, the segmented encapsulated mirrors, and the collector frame. Dimensions given in these drawings were part of the original design and some were revised in the final design.

A. Evacuated Tubular Receiver

Figure 4 showcases the schematic of the single-wall evacuated receiver tube, which was specifically designed for this project. A comprehensive description of this receiver was given in the First Progress Report. One of the three receiver tubes received from the manufacturer was tested under stagnation conditions and one sun radiation density. The temperature inside the copper tubing was found to be 240°C, attesting to the excellent heat absorption and retention qualities of this receiver design.

B. Segmented Mirror

A significant part of our effort since August has been directed towards developing and building the segmented mirror. Figure 5 illustrates the final design of the mirror units. Plexiglas plastic (1/8" thick) was chosen as the material for the mirror substrate. Key considerations in this decision were ease of handling, cutting, and machining.

FIGURE -1- UNIVERSITY OF PUERTO RICO / CEER FACETED CPC COLLECTOR (EFF crx 5) (SUPPORT FRAME FOR TUBES NOT SHOWN)

Evacuated SPACE SINGLE Wall: for CYLINDRICAL ABSORBER + 2a" WITH “U- TUBE

Fluorescent TUBE BLANKS: (SEALED OFF) 0.0. +h

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Page 3A0, January 23rd, Annual Event 130, Hollywood, CA 21108. Event Announcement:

Scanners Event with Liam O'Zit14n at 3:00pm. Join us in a maze of labyrinth - fun for everyone.

Smoothness of Surface: The Plexiglas was cut into strips 7" long and 1 15/16" wide. Finding a suitable reflective film and a method of bonding it to the Plexiglas was a major problem. Much effort was spent in trying to bond 200 Oun-Chrome @, OL-50 metallized polyester film (Dunmore Corp., Newtown, Penn.) to the Plexiglas with unsatisfactory results. Many different types of bonding agents were tried.

Finally, we learned of a new product manufactured by the 3M Company. This is their "Scotchcal" Brand Film FEK-244, a 0.004" thick aluminum-on-acrylic film with 86% spectral reflectance. This film has pressure-sensitive adhesive backing and satisfactory results were obtained in applying it to the Plexiglas substrate.

The encapsulation tubes are fluorescent tube blanks obtained from Corning Glass Works (Fig. 6). These have an outside diameter of 2.08" and a wall thickness of 0.035". We estimate the diameter tolerance to be + 0.01". The mirror segments are held inside the glass tubes by spring clips at the ends.

In order to prevent undue sagging of the mirror, it was found necessary to attach three screw spacers at equal intervals along its length. A metal heat shield was also attached to prevent damage to the mirror when the glass tube was being closed off. After attaching clips, spacers, and shields to the mirror, the assembly was inserted inside a glass tube (Fig. 7).

The mirror was then checked to determine whether there was any twist of one end with respect to the other. This was done by looking at the reflection of a laser beam from the mirror at different points along its length (Fig. 8). Since one end of the mirror was accessible and since the spacers were not attached to the tubes,

Fig. 6: Fluorescent Tube Blanks from Corning Glass Works,

Fig. 7: Insertion of Mirror Assembly into Glass Tube,

A. One end with respect to the other.

"Any large twists could be removed. The largest allowable amount of twist of one part of the mirror with respect to another was 1°. Originally, it had been planned to close off the glass tubes after they had been evacuated at an elevated temperature and filled with a dry gas. The idea was to eliminate as much moisture as possible from the inside of the tubes. An oven was built, and it was determined that the mirrors could withstand 100°C without apparent damage. However, when the tubes were evacuated to a pressure of 500 microns of Hg at 100°C, immediate damage to the adhesive bond resulted. Evacuation alone did not appear to damage the bond and several tubes were made using this procedure. After being connected to a vacuum pump for 30 minutes, they were filled with dry nitrogen at a pressure of approximately 1 atm. Damage to the adhesive bond of these mirrors did not become apparent until they had been exposed to sunlight for 2 to 3 weeks.

Finally, it was decided to abandon the evacuation procedure. Tubes were closed off in an air-conditioned room. A room dehumidifier brought the relative humidity down to 50% at 75°C, which corresponds to a ratio of moisture to dry air of 1.0% by weight. Another important problem encountered in the construction of the tubes was the frequent breakage and cracking.

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A total of 213 units of the glass at stress points where it had been worked. Since the temperature of the mirrors could not be raised, it was not possible to do oven annealing to relieve these stresses. This problem was alleviated considerably when the evacuation procedure was abandoned. It seems that a large part of the problem was due to differences between..."

The nitrogen pressure inside and the atmospheric pressure outside resulted in uneven tips, which eventually cracked. Figures 3 and 9 show the collector frame, including the tube wells that hold the glass tubes. The basic dual axis tracking frame design developed by the University of Chicago was altered in some important ways. The main beam of the frame, which in the Chicago design was a T-beam, was found to be too unstable to withstand torsional forces such as would be exerted on it by the collector weight when tilted. The T-beam was replaced with a rectangular cross-section hollow beam, which also allowed for a simpler design for fixing the beam to the circular platform. Four bolts were added to the sides of the main beam to prevent movement of the circular platform (and thus the collector) after it has been set at a particular position. To measure the collector's tilt angles, two bubble level protractor assemblies were installed at each end of the collector frame. These permit angle measurements with an accuracy of approximately 1/4 degree.

Major efforts on the collector frame went into designing and building the tube wells, which are shown in detail in Figure 9. A computer program was developed to calculate the theoretical shape of the reflector surface (see First Progress Report, Appendix B). Using the results from the program, the tube wells were precisely machined. Four identical pieces (each was one-half a well) were machined simultaneously by stacking them. The raw material for the wells was four pieces of 1/2" aluminum, 20" wide and 48" long. The circular holes that hold the tubes have a diameter of 2.09". The straight-line distance between circles is 2.11" to allow for the metal bands that grip the tubes. After the tube holes had been machined, excess material was removed to make the structure lighter. The tube holes thus became open semicircles. Figure 10 is a depiction of the support bar and the structure which holds the receiver tube.

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The features can also be observed in Fig. 9. Two halves of a welt were held together by precisely machined pressure fit pins, screws, and nuts which joined them to the support bar. The pressure fit pins assured alignment to a high degree of precision. The receiver tube is supported by a structure that allows space for the mirror tubes that are positioned closely to the receiver. The mirror tube wells are fastened to cross support members of the frame. Six aluminum tubes connect the tube wells to each other. These add much rigidity to the structure.

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And add very little weight. The structure for fastening the glass tubes to the wells is shown in Fig. 11. It consists of a stainless steel band which is pulled tight by a screw running through a bolt fastened to the frame. The bands are placed so that bands from neighboring tubes do not touch, thus reducing the distance between mirror segments.

Title: Analytical Studies of Collector Orientation

One of the main advantages of a CPC design is the possibility of eliminating continuous tracking of the sun, thus reducing complexity and cost. This is because a CPC can collect radiation incident over an extended range of angles as shown in Fig. 12. Our CPC design is an ideal 6.30 X concentrator truncated to 5.25%. The theoretical half acceptance angle (θ,) of the ideal concentrator is 9°. An actual device never has a perfect theoretical shape due to random deviations of its surface from the "ideal" surface. This changes its acceptance characteristics (see Fig. 12), but this change can be approximated as a reduction in the acceptance angle. The idea, then, is to orient the collector so that the radiation is incident at an angle less than or equal to the acceptance angle. Yet, we want to do this with a minimum amount of tracking. The optimum collection to tracking ratio is achieved by orienting the long axis of the collector along the fastest direction. The angle of interest is then the projected incidence angle on the plane defined by the

Zenith and the

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EFFICIENCY OPTICAL

The fraction of the radiation incident on the aperture of a CPC at angle @' which reaches the absorber. ATT curves refer to a concentrator in two dimensions with an acceptance half angle 0, assuming perfect reflectivity.

Untruncated idea concentrator
Truncated idea concentrator
Untruncated concentrator with average surface error 4.

North-South direction. This angle (0, measured from the zenith) can be calculated for a particular day and hour by the following formula tan (0, +a) = tan 8 / cosy where a is the latitude, 6 is the declination and w is the angular time from noon (w = 2nt/24, t in hours).

Fig. 13 is the graph of O, for different days during the year and for Puerto Rico's latitude. A scheme for orienting the collector can be derived from this graph. One first chooses a half acceptance angle (0.) and a minimum daily collection time (e.g. 7 hours/day).

Starting at the summer solstice, one determines the value of 6, at the extremes of the minimum collection time (time=3.5). Call this angle @,. Before and after the solstice the collector would be oriented at an angle 0,-0.. For this configuration, the collector would have a high optical efficiency at any hour of the day that 0,-20,<8,,<0,.

For several days after the solstice this condition will hold more than 7 hours a day. But there comes a day when it will hold for less than the required 7 hours because it will not hold in the period around noon time. On this day, the collector orientation should be changed.

Suppose that the value of O,, at the extremes of the minimum collection time on this day is @). The collector is then pointed at an angle @:-@.. This procedure for determining the collector orientation and the dates for changing it is repeated until a full year is mapped out. The result is a chart such as the one

Fig. 13 PROJECTED SOLAR

Elevation (For Latitude 18.5) Days from Solstice: 7, 2, 3, 4, 5, 6 Time (Hours After Noon) -21.

22, as shown in Table 1. For a half acceptance angle of 9° and a minimum required collection time of 7 hrs./day, the collector has to be reoriented only 10 times a year.

IV. Insolation Measurements

Solar radiation has been recorded at the Bacardi plant in Cataño since July 1978. Both diffuse and total insolation have been recorded. Details of the measuring process were given in the first Progress Report. Results of the computer analysis of data for the months of July, August, and September are given in Appendix A. Data for the months of October, November, and December show certain irregularities, which are not understood at present. These months are not included in the Appendix.

V. Conclusion

The completion of the construction of an innovative experimental solar collector designed for industrial steam generation is the main achievement of our work this year. In addition, much analytical study of the design has been made and a solar radiation measuring program has been implemented at the proposed industrial site. The analytical studies indicate the possibility of a high efficiency to cost ratio for this collector. Figures 14, 15, 16, and 17 are views of the finished Bacardi solar collector.

"82" G24 Data Series 02 etc. are not clear and seem to be in a different language or code.

Fig. 14 Complete Bacardi Collector

Fig. 15 Complete Bacardi Collector of One Tube Structure. Close-up View Well and Related

Support

Fig. 16 Complete Bacardi Collector.

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