SECONDERY CONCENTRATOR FOR A COMMERCIAL SOLAR RECEIVER SYSTEM – DESIGN AND EVALUATION

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Abstract

A 1 MWt Solar Electricity Generation Demonstration Plant test facility is scheduled for operation early next year. The plant includes a large compound parabolic secondary concentrator. Strict requirements led to a unique modular structural concentrator design. The design allows for close tolerances and ease of assembly and maintenance. Special attention was given to the thermo-mechanical design, and to the selection of reflecting surfaces and method of attachment. Calculations have shown that stresses within the glass mirrors can be controlled with proper design.

Introduction

A Solar Electricity Generation Plant test facility is about to be erected next to the solar tower of the Weizmann Institute of Science (WIS) in Rehovot, ISRAEL [1]. The project is a joint venture of Rotem Industries, Ormat and WIS as part of activities within the CONSOLAR Israeli solar consortium. The facility will serve as a test platform for a larger commercial solar plant which is due to operate by the early years of the next century in Arizona, USA. The test facility shall utilize part of an existing 3450 m^2 heliostat field. The radiation shall be concentrated onto a tower reflector (hyperbolic mirror) which in turn will direct the energy straight down into a secondary Compound Parabolic Concentrator (CPC) and 10 peripheral lower temperature CPC's. The concentrated radiation enters the aperture of a high temperature volumetric receiver (Fig.1).

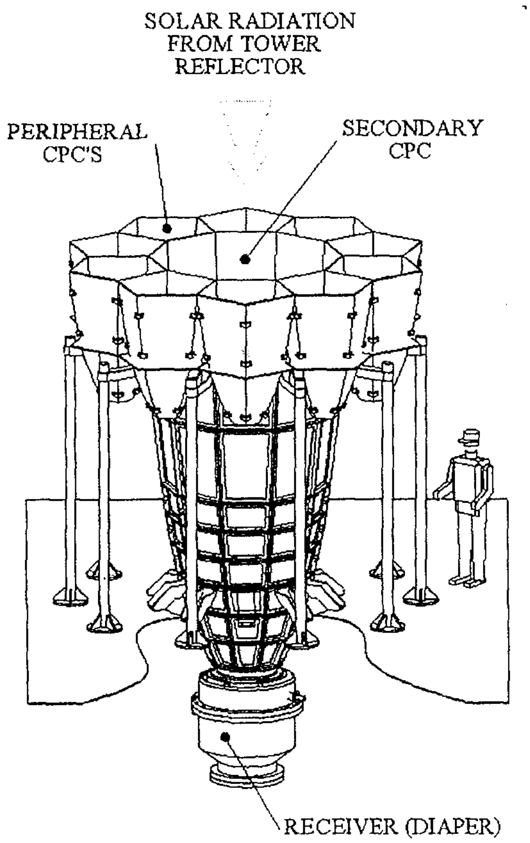

Fig.1 - CPC's/Receiver arrangement (Heliostats, Tower Reflector and Turbine are not shown).

The receiver is a Directly Irradiated Annular - Pressurized Receiver (DIAPR) [2] with an inlet aperture diameter of 460 mm. It absorbs around 520 kW of a total of 640 kW solar energy, which enters its aperture. The receiver contains a "porcupine" shaped ceramic bed to absorb and transfer the energy to high pressure (22 Bar) - high temperature (1200-1300 °c) air. The air is then fed into a high temperature gas-turbine/generator unit to produce electricity.

Compound Parabolic Concentrators (CPC's)

In order to achieve the high concentration rate, which is essential for the system performance and efficiency, a secondary CPC, which is based on Non-Imaging Optics principles, is used [3].

The secondary CPC is positioned on top of the DIAPR with its inlet aperture plane pointing upwards to accept radiation from the Tower Reflector. Solar radiation of 750 kW enters the 2.2 m diameter CPC aperture that is truncated to 5 m height. It was obvious at an earlier stage that such a big concentrator could not be practically made to fit the theoretical curvature and still be economical and maintainable. Ray tracing optical analysis suggested approximation of the parabolic profile by ten flat segments with only 2% power loss. The first bottom section is 200 mm high, the next six are about 350 mm high each and the three top ones are 900 mm high each. Ten peripheral CPC's are installed at the perimeter of the secondary CPC to collect the lower energy spillage of the radiation. In order to efficiently collect all the energy at the CPC's entrance, a decagon shaped cross section was chosen for the central CPC, and pentagon shaped cross section for the peripheral ones (Fig. 1).

Design Requirements and Concept

Several requirements and restrictions bound the mechanical design. The structure has to be rigid and self-supported, on the other hand light and easy to manufacture, assemble and maintain. It should support the reflecting surfaces, provide cooling to working temperature with minimal thermal stresses, and allow for thermal expansion. It was required that any of the reflecting surfaces could be replaced without dismantling the whole structure. Tight dimensional tolerances were dictated with minimal misalignment between adjacent reflecting surfaces. The

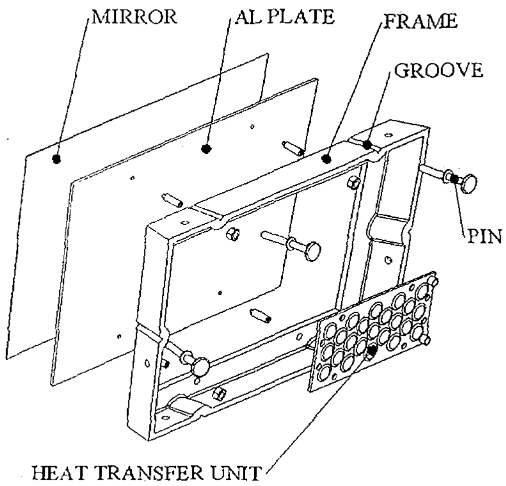

Fig. 2 - CPC's Module – Exploded Rear View.

design has to be carried out with view to the larger commercial plant, which shall be based on the current concept. The design concept was selected after investigating existing CPC's, e.g. [4] and [5]. No CPC of that size was found. Previous concept of a CPC that serves as a 50 kWth prototype for this project was found to be inapplicable due to manufacturing limitations and cost.

Eventually the selected concept was decided upon (Fig. 1, 2). It comprises ten different size modules; each made of aluminum frame casted to near final dimensions (Fig. 2). The frames are machined to precise dimensions only on limited groove shaped areas, thereby saving on production costs. The frames are bolted to each other with cylindrical 10 mm diameter pins placed at the grooves. The groove/pin assembly allows for a 2 mm gap between the frames and enforces close dimensional tolerances on the complete structure. Ten similar frames bolted together create a complete decagon shaped closed ring. Ten rings are mounted on top of each other to complete the whole CPC structure. While being a closed, rigid self-supporting structure, it allows for backside disassembly of any single frame. Pulling first the pins, the frame is free within its surrounding 2 mm gap and is easily taken out without interference to the rest of the CPC.

The reflecting surfaces are thin back silver-coated glass mirrors glued to 6 mm thick aluminum plates, precisely trimmed to dimensions and bolted to the frames. Commercial plate-type water-cooled heat transfer units are attached to the back of the aluminum plates on the lower sections where heat fluxes are high to dissipate the absorbed heat.

Thermal and Thermo-Mechanical Design

In order to determine the thickness of the mirror and the silicon adhesive, thermal and structural calculations, including the Finite Element Method (FEM), were carried out for the reflecting panels at the specified thermal and environmental conditions. Fig. 3 shows the CPC profile and the solar heat flux distribution on its panels.

A Portion of the solar radiation (up to 10%) is absorbed in the reflecting coating of the mirror and heats the panels. In addition to the solar heat load, the radiative heat flux from the receiver aperture is absorbed on the outer face of the glass. The heat transfer unit that is attached to the rear side of the aluminum shall keep the mirror and the adhesive within their service temperature limits. The low thermal conductivity of the adhesive layer leads to high temperature differences between the glass and the aluminum. The difference between the thermal expansion coefficients of the aluminum and the glass causes stresses in both components. The stresses in the glass, which is the sensitive component, can be minimized by optimal selection of the glass (coefficient of thermal expansion, absorption, thickness, etc.) and the adhesive layer (thickness, thermal conductivity, service temperature, etc.).

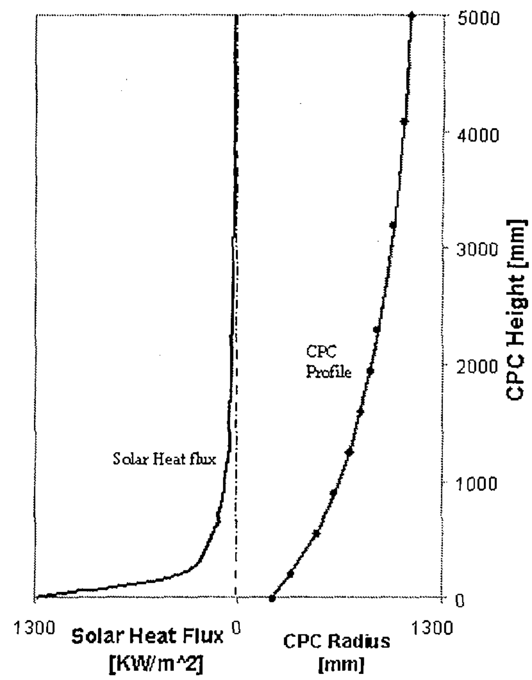

Fig 3 - CPC profile and the solar heat flux distribution

After preliminary investigation, two types of glasses were selected for further analyses - Glaverbel VERTEC and Schott BOROFLOAT glasses. Calculations were carried out to optimize the glass and adhesive parameters.

Fig. 4 shows the thermo-mechanical model and its boundary conditions. The thermal and mechanical properties of each component were taken from the manufacturers data sheets and are given in Table 1. As first approximation, analytical calculations were done assuming one-dimensional expansion at zero stresses (i.e. the strains of the glass and the aluminum are set to be equal). The required adhesive thickness for this case for both glasses is shown in Fig. 5. One can see that the VERTEC glass requires thinner adhesive layer, which will ensure lower temperature in the glass. More detailed analyses were done using the Finite Element Method. In order to simplify the analyses, two-dimensional model was built, assuming plane strain and large strain behavior. The calculations were carried out for the lower panel that is exposed to about 1.3 MW/m^2 solar radiation on its base, and the highest re-radiation from the receiver aperture. For each glass, thermal analysis was performed to evaluate the temperature field across the panel. The results of the thermal analysis were applied as loads on a FEM model of stress analysis. The results show that the stresses

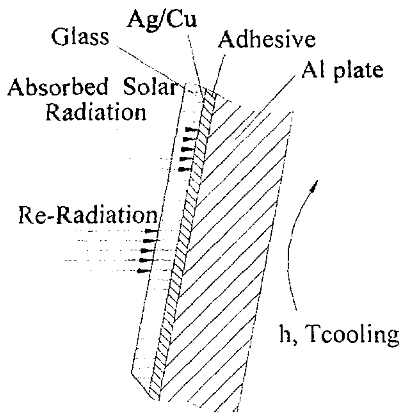

Fig 4 – Thermo-Mechanical model of a panel.

Material	VERTEC glass	BOROFLOAT glass	Adhesive (Silicon)	Aluminum
Thermal Conductivity [W/m K]	0.95	1.13	0.147	150
Young Modulus [GPa]	70	64	0.01	72
Poisson Ratio	0.23	0.2	0.45	0.3
Linear Thermal Expansion [1/K]	$8.5 \cdot 10^{-6}$	$3.25 \cdot 10^{-6}$	$9.6 \cdot 10^{-4}$	$23.8 \cdot 10^{-6}$

Table 1 – Thermal and Mechanical properties.

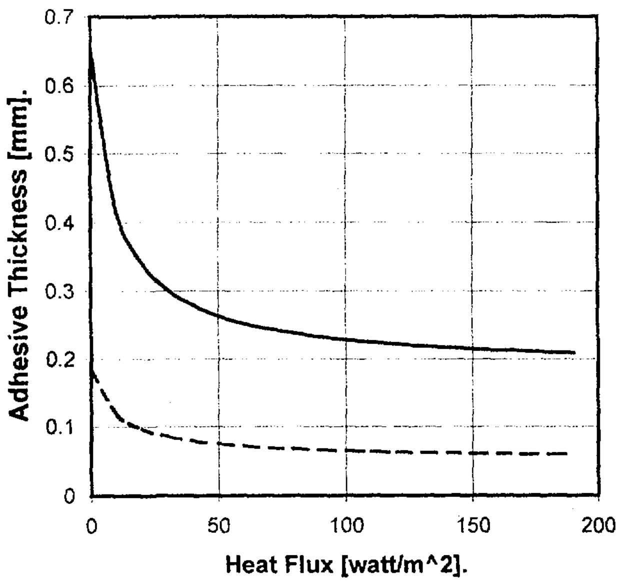

Fig. 5 – Adhesive thickness for the VERTEC glass -----, and for the BOROFLOAT glass ——, at zero stress conditions.

along the panel are homogenous, except for the last 5 mm on the edge, therefore the assumption of plane strain is reasonable. Table 2 summaries the results for the maximum tensile stress and maximum temperature in the glass, and maximum shear stress in the adhesive.

Type of Glass	Adhesive Thickness [mm]	σ_{max} Glass [MPa]	τ_{max} Adhesive [MPa]	T_{max} Glass [°C]
VERTEC	0.1	-22.6	0.2	188
	0.05	-12.6	0.1	137
BOROFLOA	0.1	12.6	-0.1	184
	0.05	21.7	-0.3	133

Table 2 – Summary of the FEM results.

The results led to the final design with the Vertec glass and 0.05 mm adhesive thickness. This combination will ensure stresses and temperatures within the service conditions of the glass, the adhesive and the reflective coating. Gaps of 0.2 to 0.3 mm are kept between the mirrors to allow for thermal expansion. A full-scale model of nine frames and reflecting surfaces is now being assembled for tests and evaluation, before the complete CPC is constructed.

Summary

The larger CPC ever built, to our best knowledge, is under construction. A new conceptual design has been applied to provide an economical device that allows simple assembly and maintainability. Extensive heat dissipation by water-cooled aluminum panels is imposed by the high radiation. An optimal combination of glass mirror, adhesive, and aluminum substrate is recommended to keep the mirror at allowable temperature, and still eliminate high tension stress in both the glass and the adhesive. Solar radiation fluxes up to 1300 kW/m^2 can be safely supported by this design.

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