The Development of a Volumetric Solar Thermal Receiver

An Overview

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I. Introduction / Background

Solar energy has received much interest in recent years, being a clean (free of pollution or other environmental damage) and inexhaustible energy source. It is also considered safer than some other nonconventional energy sources (like nuclear energy). The interest in solar energy is motivated mainly by the growing awareness of the environmental problems associated with the use of conventional fuels.

However, solar energy may become a serious alternative only if it can be used efficiently in major energy consuming industries (like the chemical industry), or be used for electricity generation. Those facilities are nowadays solely dependent on fossil fuels as the prime source of energy.

The solar energy, reaching the earth in the form of radiation, can be utilized either by direct quantum conversion using photo-voltaic solar cells, or by converting the radiation into thermal energy, to be used directly for heating, or to feed a thermal to electric converting cycle. After three decades of huge spending on the development of photo-voltaic systems those devices are commercially competitive only on a very small energy scale, while solar thermal commercial applications are more attractive.

Prominent examples are the domestic heating water receivers (direct thermal), and LUZ International electricity generation plants which are currently operated on a commercial basis, supplying 80 MWe per plant. Direct thermal exploitation of solar energy is naturally more efficient than converting to electricity, but is limited to specific applications and locations especially since thermal storage at high temperature is not commercially viable. Efficient electricity production at a competitive price is clearly the biggest opportunity for solar energy.

II. Solar thermal electricity generation

The efficiency of any solar thermal electricity generation plant depends on the efficiencies of energy collection, conversion from radiative to thermal, and conversion from thermal to electrical energy. The last factor is governed by the commercially available "power blocks" based on steam or gas turbine. The efficiency of those is directly related to the inlet temperature (a fraction of the maximum efficiency - Carnot cycle). Steam power converting units are limited to inlet temperatures of 550°C, reaching typically 34% efficiency. "Combined cycle" converting systems consist of a gas turbine with an inlet temperature of up to 1350°C for the upper cycle, and a steam turbine for the bottoming cycle (Fig. 1). Such modern systems are already approaching the 60% level of efficiency.

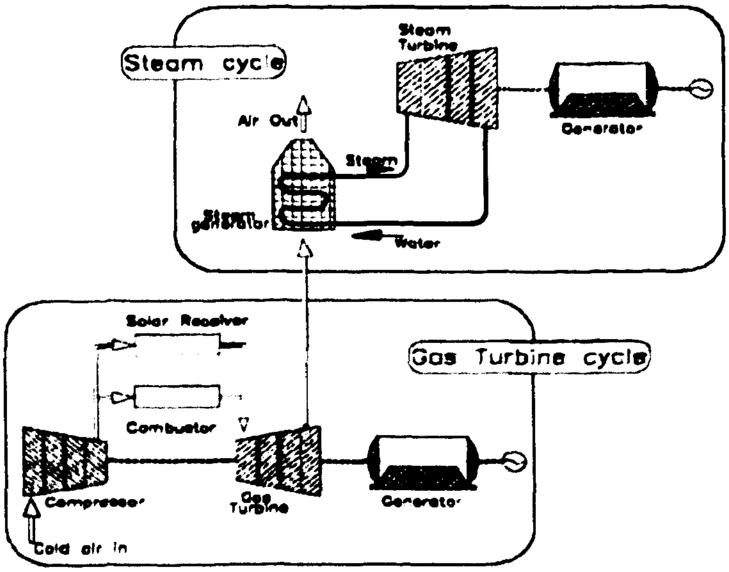


Fig. 1: A Solar-Fossil Combined Cycle Scheme

The existing solar thermal electrical generation technologies are inherently limited in their potential efficiency due to their limited temperature. The only present commercial technology, developed by LUZ, uses oil or water as the working fluid, and is hence limited to 350^oC for the operational plants. The American technology, intended to be demonstrated by 1998 in the Solar 2 project, uses molten salt as the sunlight absorbing fluid and then uses a heat exchanger to generate steam, at 550^oC at most. The existing technologies can therefore support steam turbine only, with the corresponding low efficiency.

LUZ technology utilizes parabolic trough reflectors (one dimensional concentration) arranged in series. The heated fluid has a long distance to flow before being used, leading to compression and thermal losses. Solar tower is a promising alternative technology overcoming the above mentioned disadvantages of the trough technology. Here a central solar receiver is stationed at the focus of an array of heliostats, exposed to the concentrated solar radiation reflected from them. The sunlight is concentrated in two dimensions and large quantities of solar power (100 MW or more) can be harnessed by a single unit.

Using secondary concentrators, concentration ratios of 2-10 thousands can be attained and therefore, a working temperature in the range of 1200 - 1500^oC can be reached efficiently in the receiver (fig. 2).

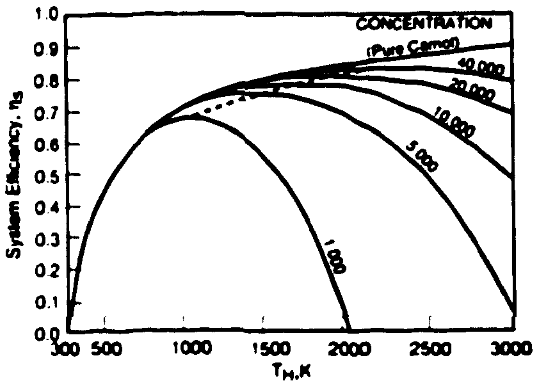


Fig. 2: "Fletcher Curves" -Heat To Mechanical System Efficiency for Various Temperatures and Concentrations

Several experimental solar towers have been built in the last three decades. The experience gained with them indicates that the key component to the plant performance is the receiver, i.e., the unit which absorbs concentrated sunlight and conveys its energy to a working fluid.

Various receivers have been proposed and were developed over the last years; they can be classified in two main (and diverse) groups:

Tubular receivers:

-The working fluid flows inside metal or ceramic tubes whose outer surface absorbs the solar radiation. The tubes can be arranged on a flat panel at the focal plane of the heliostats, or ,de a cavity.

Volumetric (Directly Irradiated) receivers:

-The working fluid either absorbs the radiation directly, or is in contact with a solid surface which absorbs the radiation. The absorbing surface may be a stationary matrix or moving particles. In some directly irradiated receivers the absorbing matrix is exposed to the ambient, while others have a window, which enables operation under elevated pressure, and utilization of other working fluids besides air.

The volumetric receivers have inherent advantage over the tubularones by eliminating the thermal gradient over the tube wall which is the limiting factor for the tubular receivers. Thus, they are able to absorb higher solar fluxes, and operate at higher temperatures. Moreover, volumetric receivers have high local heat transfer rates, which, together with the flux capability, result in compact and cheaper receivers.

Clearly, operation of the receiver under pressure is imperative for practical utilization since the fluid has to be expanded in the turbine at its nominal inlet pressure.

Alternatively, the fluid has to be pumped through heat exchanger with lower pressure drop, but loosing a few tens of degrees in addition to high extra expenses.

The development of a dependable window for a volumetric receiver, capable of sustaining high pressure and temperature, has been highly desirable by many groups but yet unsuccessful.

In the following we present a new program aimed at the development of a volumetric solar receiver capable to absorb very high solar flux efficiently, to heat air to the temperature and pressure required to feed modern gas turbine plants. The project is carried out by researchers and engineers at the Nuclear Research Center - Negev (NRCN) in collaboration with scientists at the Weizmann Institute of Science.

The commercial aspects of the program are managed by Rotem Industries Ltd. for NRCN and by Yeda for the Weizmann Institute. Part of the CED calculation were carried out at the Advanced Technologies Center in Temed Park.

III. The Porcupine Receiver:

A schematic view of the proposed receiver is presented in figure 3.

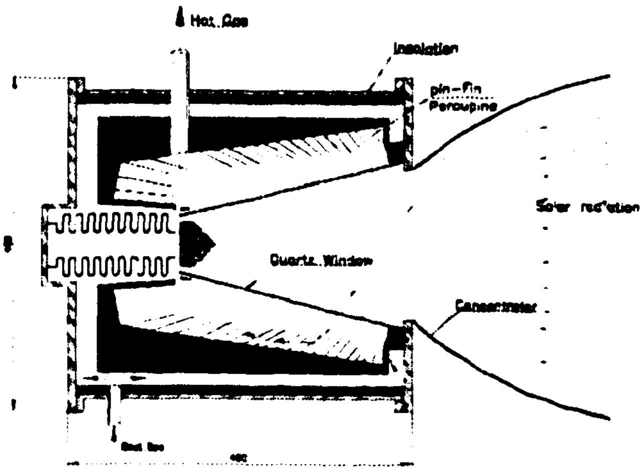


Fig. 3: A Schematic Layout of the "Porcupine" Reciever.

Sunlight reflected from the heliostats field is further concentrated by the secondary NonImaging Concentrator,then enters the receiver aperture and is absorbed by the "Purcupine" absorber. The energy is transferred to air flowing across the receiver's pins. A secondary air jet cools the quartz window before joining the main air stream. Heat losses through the receiver's casing are minimized by passing the air over the receiver's outer circumference before injecting it into the receiver's chamber. Control of the temperature distribution within the receiver, the air exit temperature and the resulting thermal efficiency are obtained by manipulating both the total mass flowrate of the gas and its distribution between the inlets.

The three main components of the receiver are:

- 'Porcupine' type volumetric absorber matrix.
- High pressure window.
- Integral secondary concentrator.

1. The 'Porcupine' Absorber:

The "Porcupine" type absorber concept was developed by the Weizmann Institute (Karni and Rubin, 1990&1991). The basic idea is to absorb the solar light over the surface of an array of pins or small tubes. The working fluid flows across these tubes, which enhances the rate of convective heat transfer from the absorber matrix to the fluid. The concept was demonstrated by WIS at their "Solar Furnace" facility (fig. 4), which, by a single heliostat that directs the light onto a 7m diameter parabolic mirror, concentrates up to 12KW of sunlight over an about 10cm diameter target.

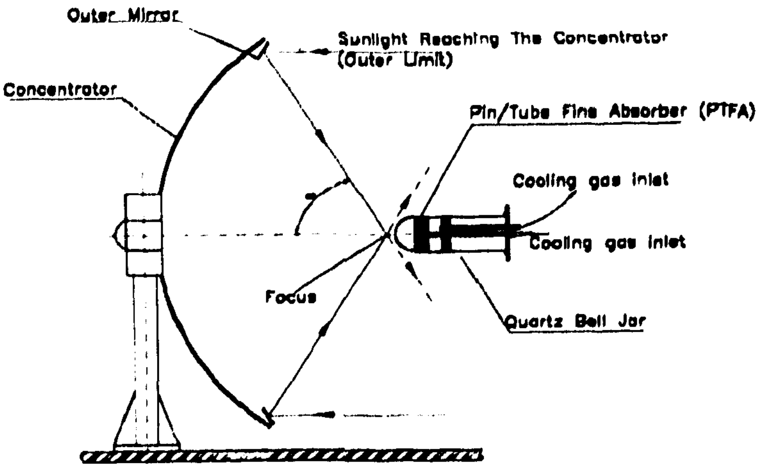


Fig. 4: A Schematic View of the "Solar Furnace" Facility

The experimental model (Fig. 5), subjected to a Gaussian flux distribution, was used to demonstrate that by careful design of the geometry of the tubes and of the flow pattern across them, one can match the heat absorption and transfer to obtain a very effective absorber. For this symmetrical case the absorber was able to operate under up to $5MW/m^2$ with 80% absorbing efficiency.

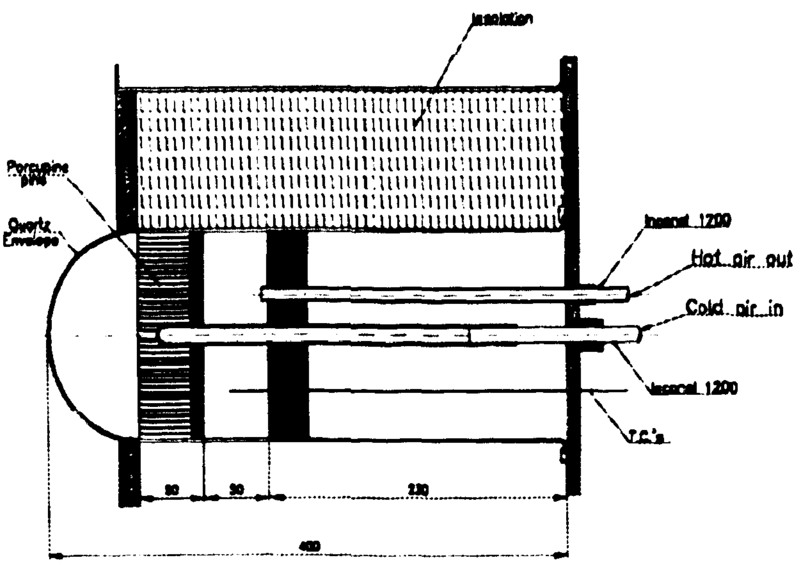


Figure 5a: A Device to Expose Various Absorbers to High Solar Flux

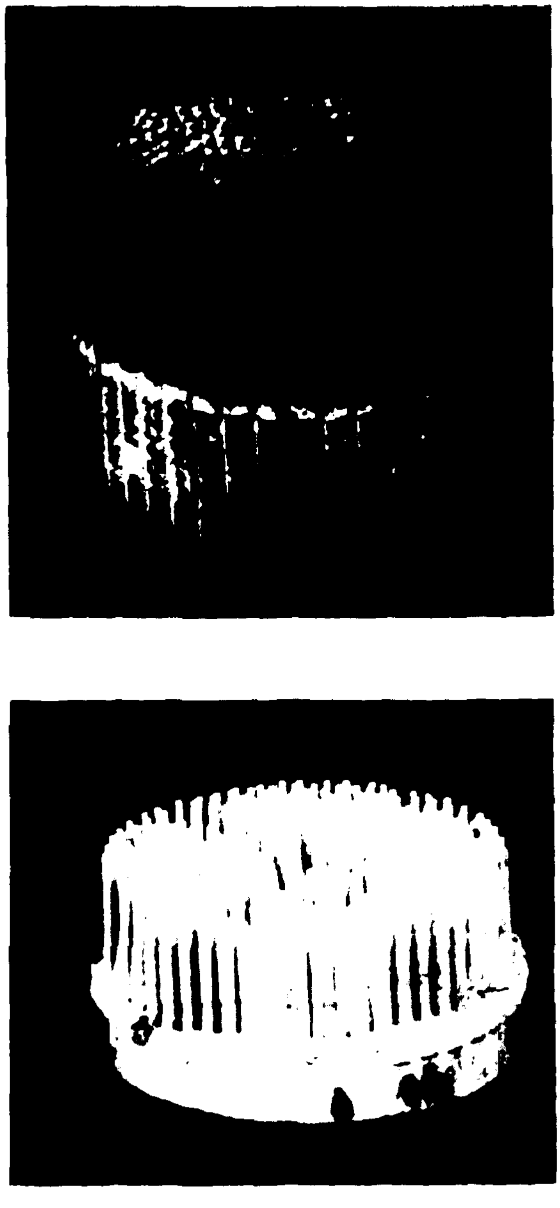


Fig. 5b: Typical "Porcupine" Absorbers for the Furnace Gaussian Flux

NRCN/WIS challenge in this project was to adapt the concept to a much larger scale, and with a different, not symmetric radiation flux distribution. Figures 6a and 6b show, respectively, a single absorber block and a bunch of a few blocks assembled together, as were developed during the program. When all the blocks are assembled together, the absorber has a Frustum shape (Fig.7), with the heat transfer elements tilted toward the axis. The general air cooling flow direction is across the tubes.

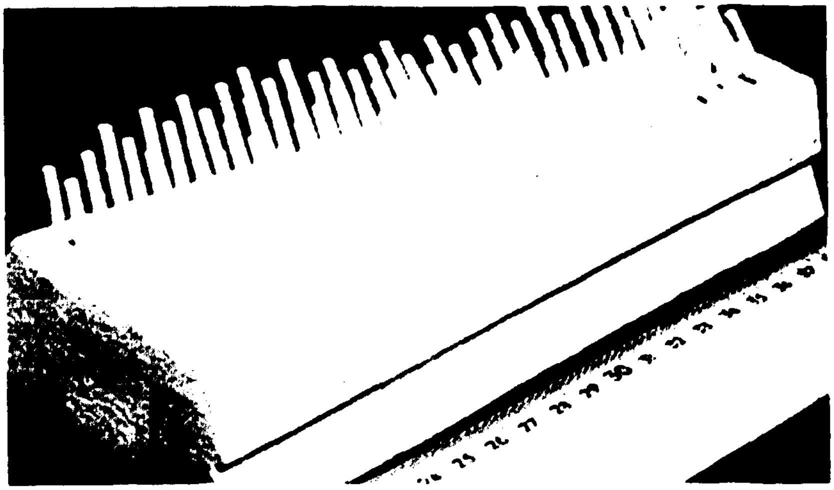


Fig. 6a: A Single Absorber Block

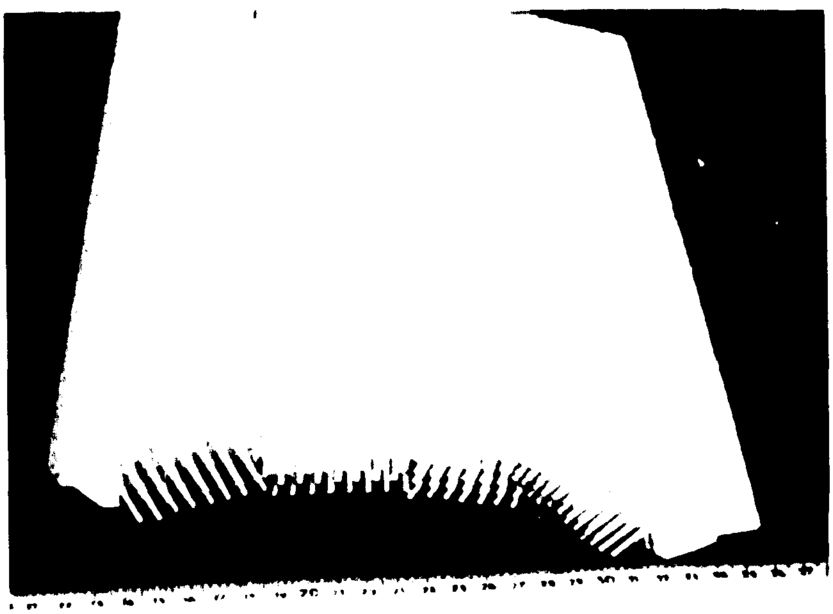


Fig. 6b: A bunch of Absorber Block Assembled Together

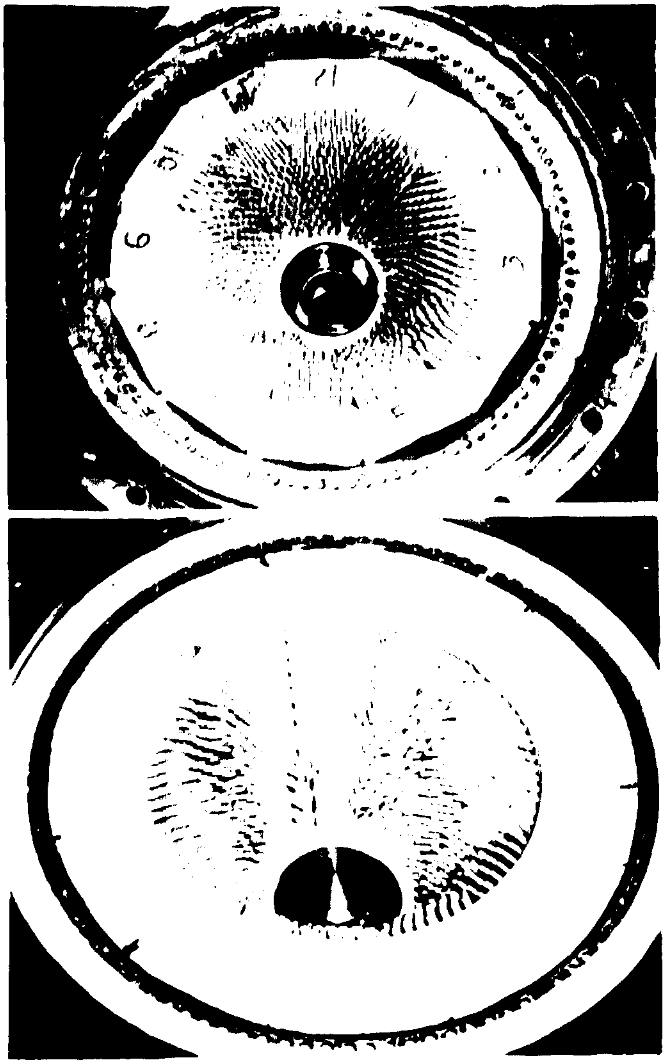


Fig. 7: The Complete Absorber Assembly within the Receiver Casing

The Porcupine absorber has the following advantages:

- The radiation can penetrate into it such that the absorption process is spread over a large heat transfer area for absorption and converting to the air.

-The energy transport along each pin and among neighbouring pins is very good.

- It provides an effective convective cooling mechanism.

- By changing the pins density, height, material, color etc, one can effectively control heat absorption and transfer balance.

- Every tube is free to strain(bend) by itself,but the assembly is free of thermal stresses.

2. The window.

The high pressure window has a frustum-like shape (Fig. 8). The window is made of fused silica (fused quartz) and, at the nominal operating conditions, supports a pressure of 15 to 30 atm at a temperature not to exceed 800°C. The two functions of the window are to seperate the receiver cavity from the ambient air allowing operation at high pressure, and to admit the solar beam minimizing reflection losses of solar radiation transmitted into the receiver. The window is cooled by the working fluid before the latter reaches the absorber. An additional gas jet cools the other side of the window and removes the accumulating dust. Computations and tests show that the window is capable of withstanding a pressure of over 50 atm, while, on the same principle a window can be designed to sustain even a pressure of 200 atm. This is achieved by assuring that tensile stresses do not develop at any possible working condition, so that the window is subjected to compression stresses only. The compression strength of fused silica is about 23 times higher than its tensile strength and about 2.5 times higher than the strength of carbon steel. The design to assure compression stresses only over the window includes, besides the frustum-like conical shape, also a unique mounting design of the window.

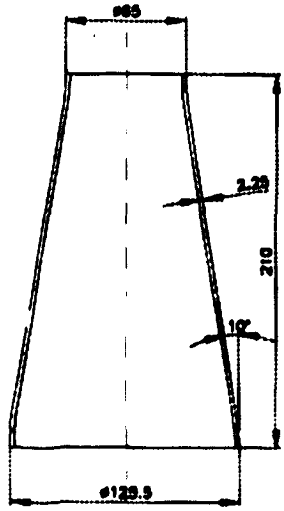
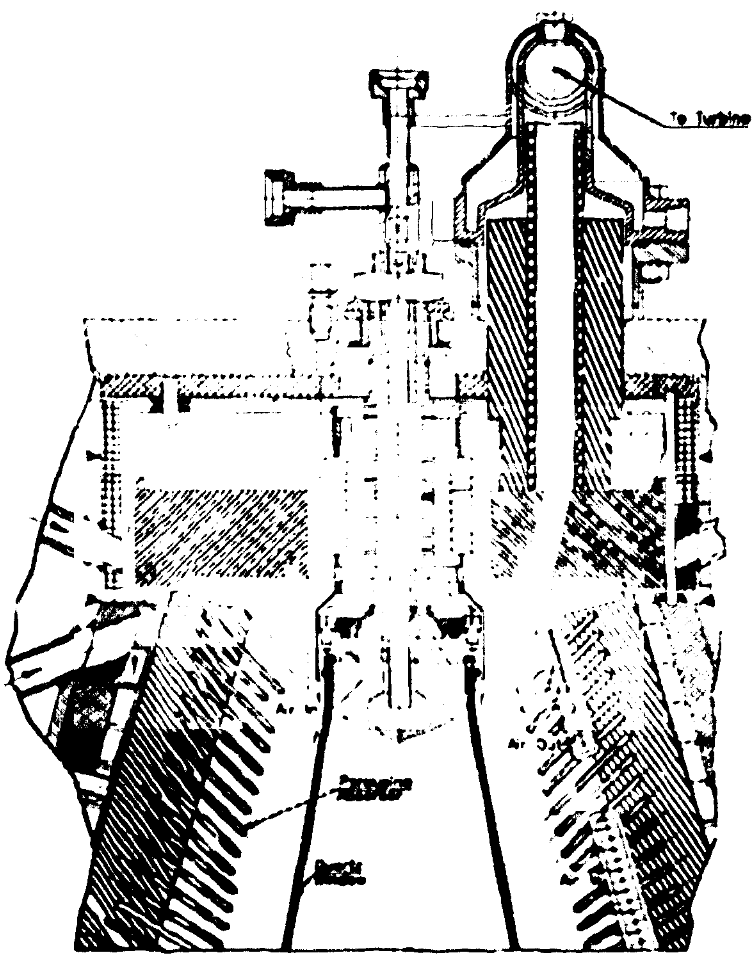


Fig. 8: The Frustum-Like High Pressure Fused Silica Window

The window wider edge is freely supported over the receiver casing frame, and is held in place by the pressure difference that provides a positive force towards the seal. The windows other edge is free to move to eliminate any stresses that might develop. The working fluid is sealed by a set of bellows (Fig. 9).

Ray tracing optical calculations indicate that the reflection losses of the window are only about 1%, since the conical shape at the selected angle traps the incoming rays. The window thickness is 2.25 mm for the present unit, making energy loss due to sunlight absorption negligible.

Fig. 9: The Window Flexible Top Support, Sealing and Cooling



3. The Secondary Concentrator:

The integral secondary concentrator is necessary to further concentrate the sunlight coming from the heliostats field to get up to 10000 sun concentration required at the receiver aperture. The actual optical element developed, combined together the concentration and the receiver optical coupling functions, to serve also as a lightguide through the receiver aperture, and light extractor within the receiver (Fig. 10).

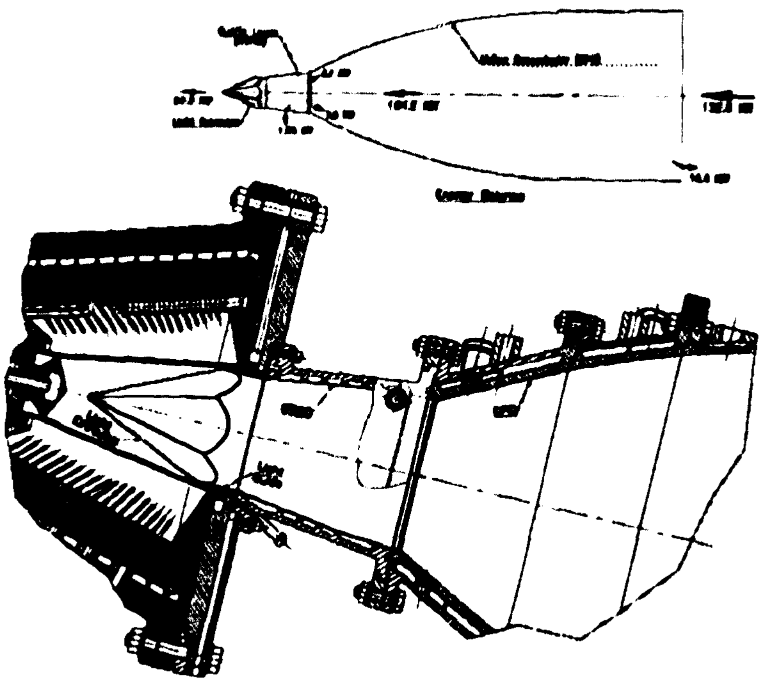
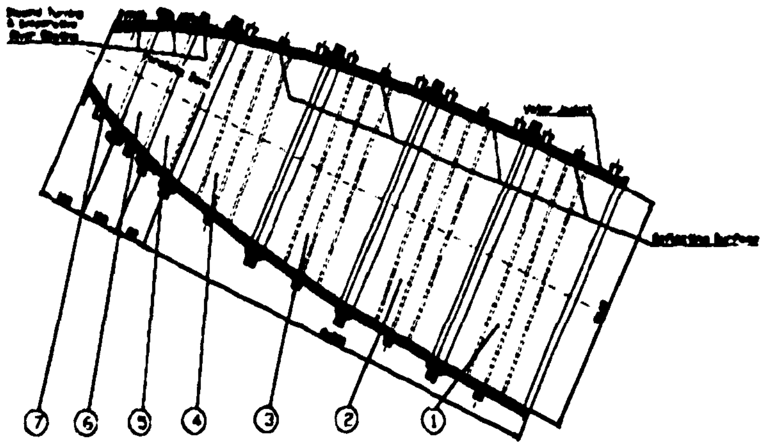


Fig. 10: The Secondary Concentrator Optical Coupling to the Receiver

The secondary concentrator is based on Non-Imaging Optics principles, and consists, essentially, of a Compound Parabolic Concentrator (CPC), optically coupled to a Dielectric Total Internal Reflection Concentrator (DTIRC).

The CPC is made out of 7 sections of double wall water cooled aluminum alloy (Fig. 11). The three smaller sections are diamond turned and front surface silver coated, with an appropriate ceramic overcoating, for abrasion and oxidation protection. The four bigger sections are lined with aluminum panels protective silver coated as above.

Fig. 11: The Reflective Compound Parabolic Concentrator (CPC)



Figures 12a and 12b are side and front views of the CPC. In the latter the heliostats in the field are seen reflected by the internal wall reflecting panels.

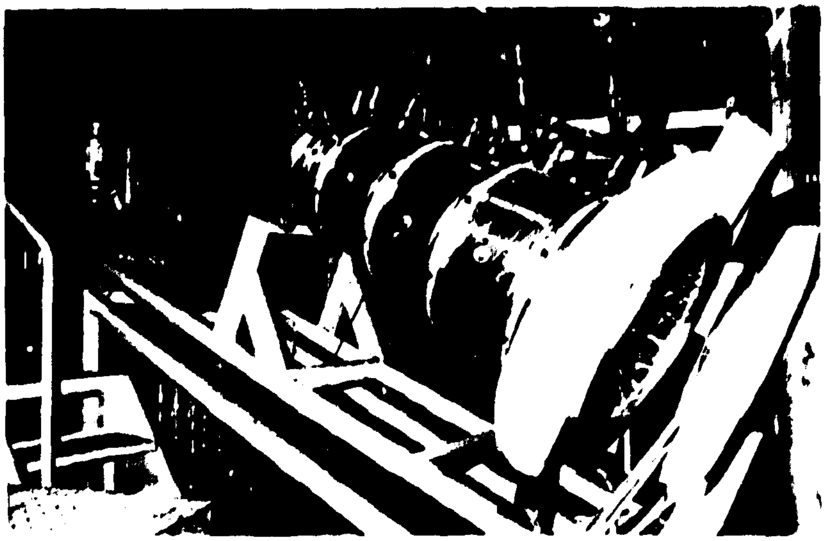


Fig. 12a: A Side View of the Concentrator

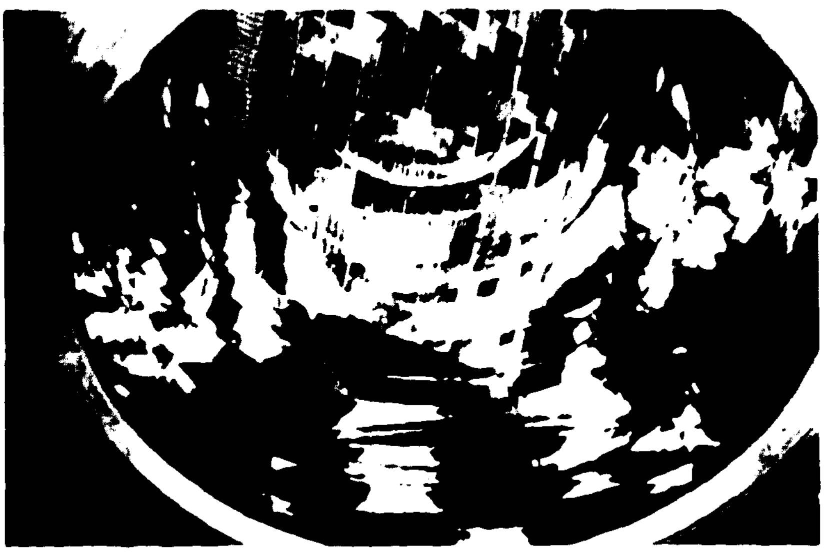


Fig. 12b: Front View of the Concentrator

Figures 13a+13b present the optical coupling element, made of fused silica. The light is concentrated in the DTIRC section, then guided with minimal losses through the receiver aperture, to be then extracted in a predesigned pattern within the receiver absorption section. The light extraction from the high index of the refraction medium (fused silica ; n=1.47) into the receiver cavity, with minimal reflection losses required a sophisticated optical design nicknamed "KohinOr" for its pyramid shape.

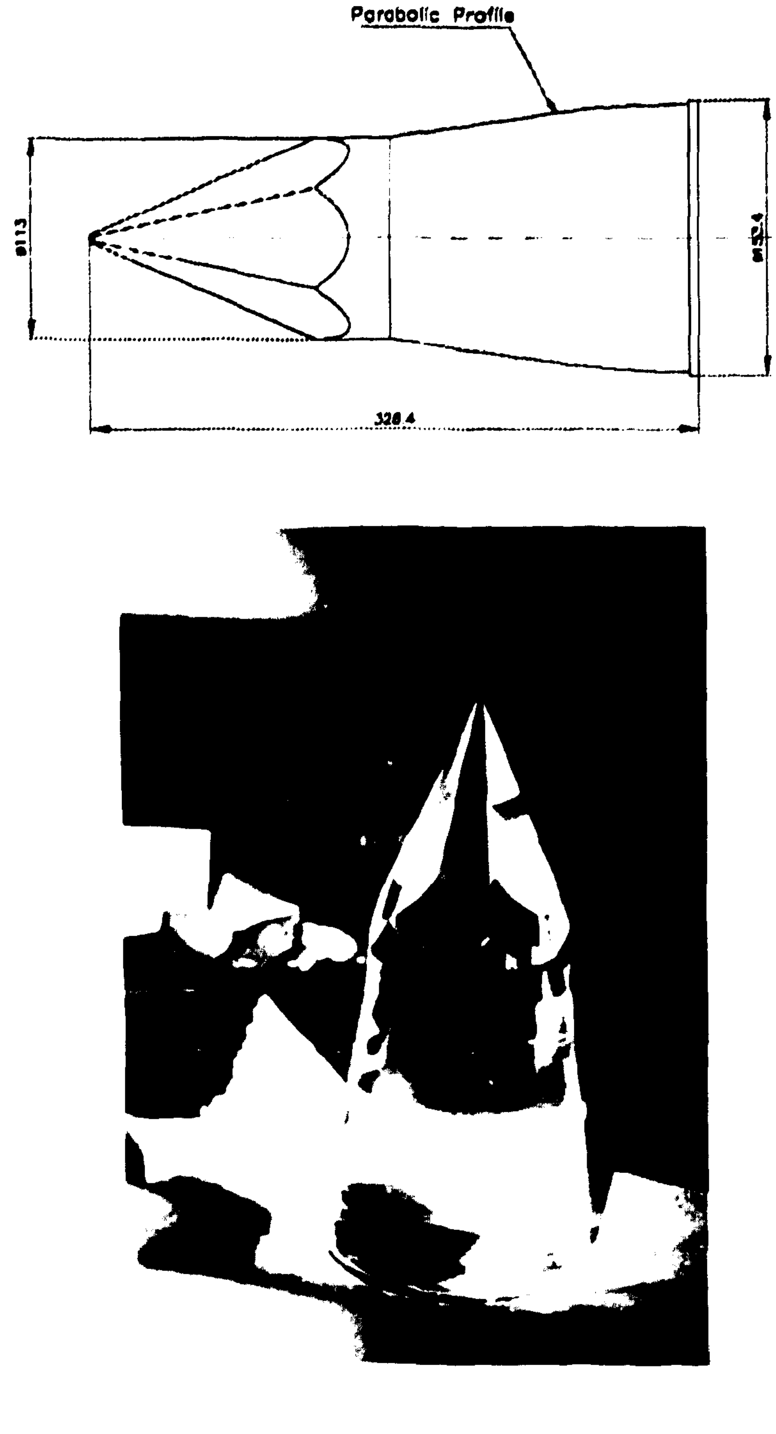
The combined reflective/refractive design has the following advantages over standard reflective-only CPC design:

- Higher concentrations can be achieved at the receiver's aperture.

-The distribution of the extracted light can be determined by the design; most of the radiation impinges directly on the absorber and the istribution of its intensity can be matched to the onvective cooling of the absorber.

- The concentrator's refractive part, where the radiation is most intense, requires relatively little cooling, since it absorbs much less radiation than a comparable hollow CPC with a reflective wall surface.

- The light extractor and the receiver's window create an annular channel, which makes the convective cooling of the window more effective.



(a)

(b)

Fig. 13: The Fused-Silica Lens

IV. Receiver Packaging:

The rest of the receiver design is a matter of practical engineering . The casing (Fig. 14) ensures compatibility with the high operating pressure while allowing introduction of measurement devices, such as pressure gages, thermocouples, etc. Convenient procedure for assembly and disassembly during the R&D phase is essential, since the receiver should be examined very frequently during the development phase to check or replace versions of absorber matrices, or flow tubes. The whole receiver unit is mounted to slide into the secondary concentrator assembly with a tenth of a milimeter accuracy to achieve the desired optical performance, and to eliminate any mechanical damage. The receiver-concentrator complex is built for fine adjustment, with special features to enable optimal alignment with the heliostat field (Fig. 15).

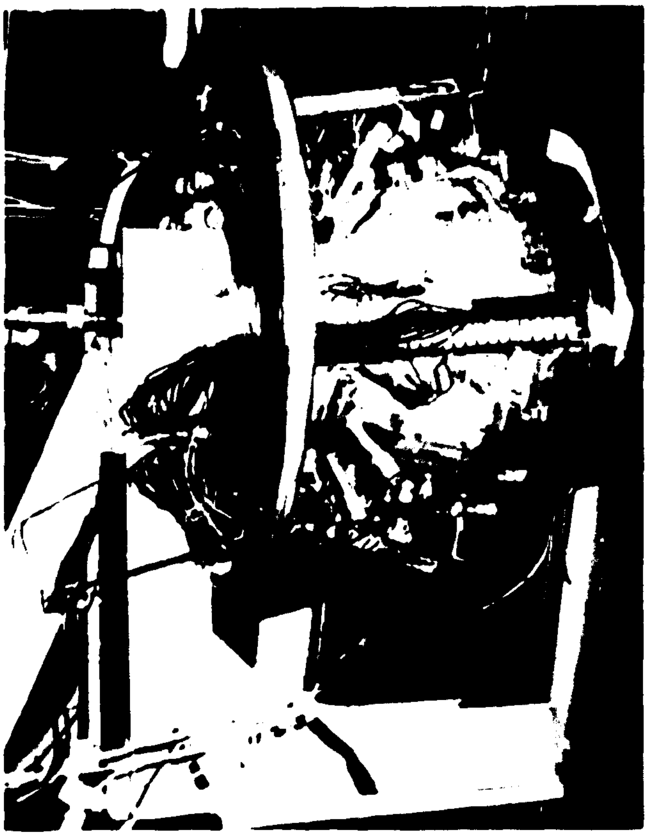


Fig. 14: An External View of the Receiver

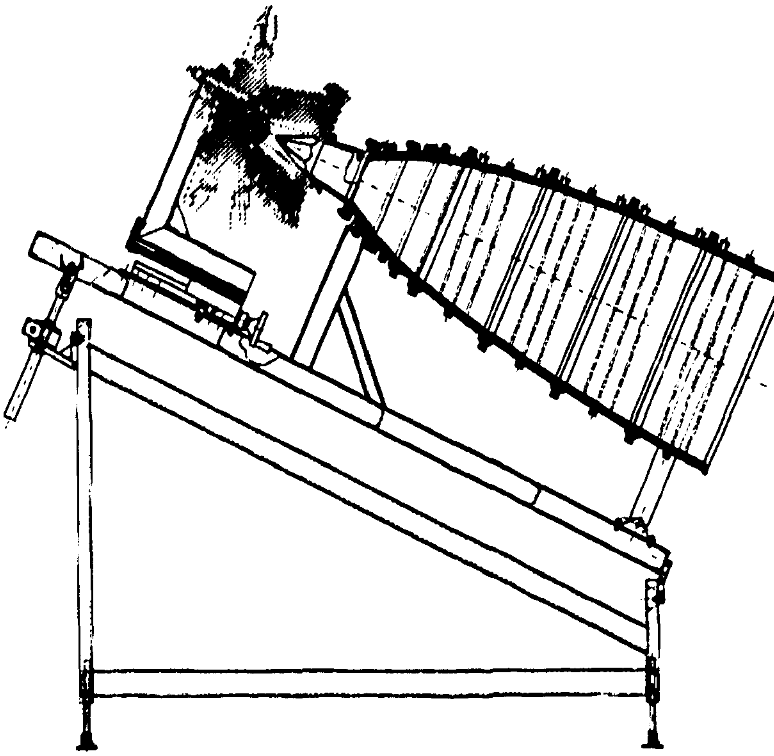


Fig. 15: The Receiver / Concentrator Complex Assembly

V. Flow field within the receiver.

The air flow field within the receiver is shown schematically in Figure 16. The air is split into main and secondary streams. Each one serves to keep cool the receiver's outer circumference before being injected into the chamber, collecting a considerable amount of heat otherwise being lost. The secondary air stream, after cooling the backside of the receiver, is used to cool the quartz window. Another air blow on the inner side of the window helps also to keep the window below the allowed 800°C. The actual receiver design with layout of the expected flow streams is shown in Fig. 17.

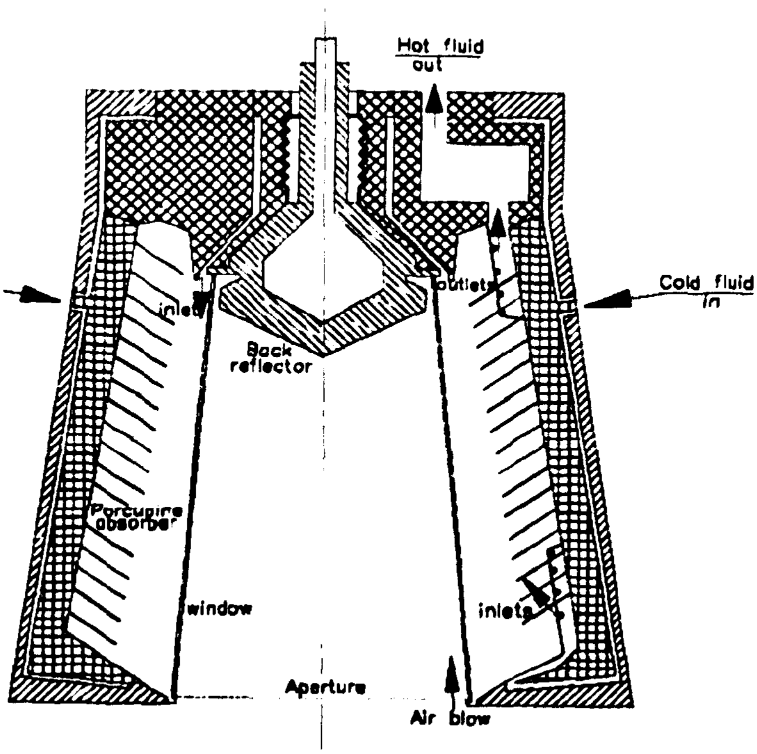


Fig. 16: Schematics of Air Streams within the Receiver

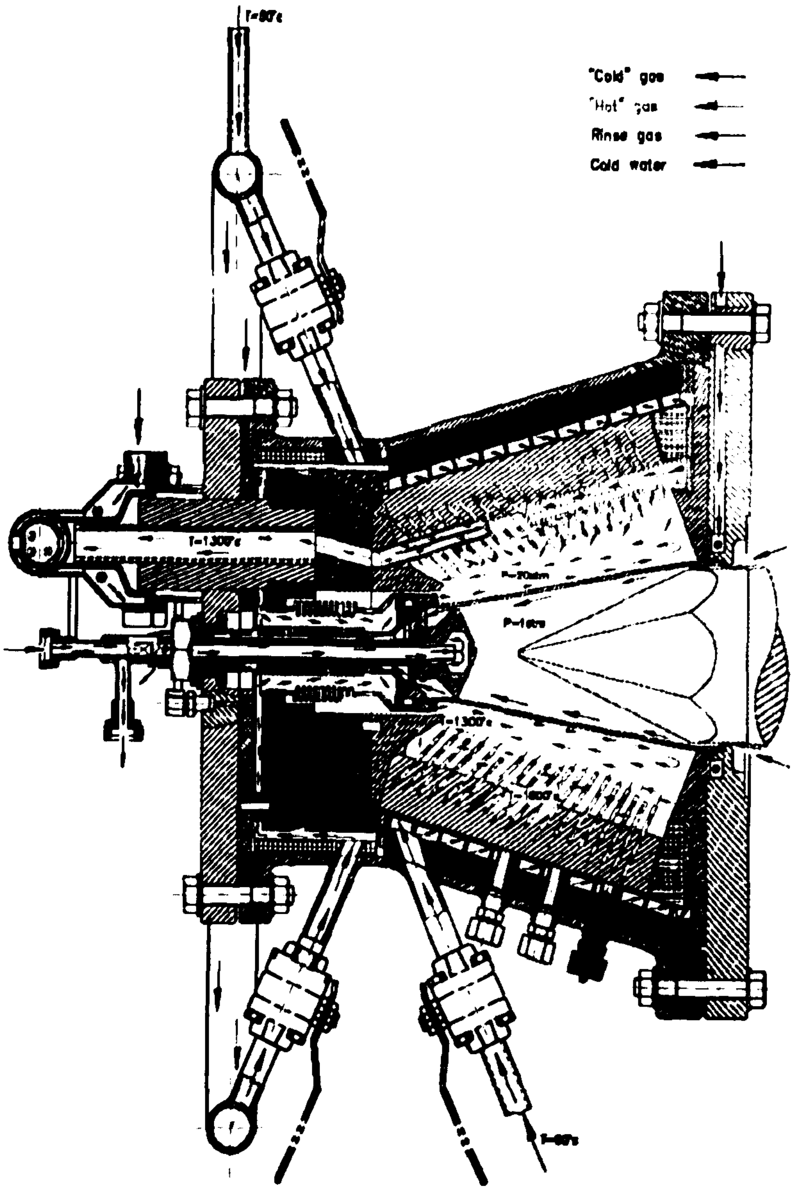


Fig. 17: Receiver Design with Air Flow Directions and Typical Working Temperatures

VI. Thermal and flow calculations.

Analysis and simulation of the thermal field, flow pattern and energy transport were initiated by the Weizmann team for the absorber development. The interpretation and expansion to the receiver geometry was performed by the CFD team at Temed Industrial Park (Rotem Industries) led by the above Weizmann team. Phase 1 of that assignment was accomplished by 1993, and further development is carried out by the Weizmann team. As demonstrated in Fig. 16 the basic receiver design provides for relatively easy modification of the flow pattern in the cavity. It is done by adjusting the location of the inlet and exit of the working fluid, and the flow parameters (velocity, flow rate,etc.) at the inlet and outlet.

The main objectives of the simulations are:

- Analysis of experimental data and indication of means to improve heat convection from the absorber to the working fluid. The simulations are compared to experimental results and are used to examine and modify the operating conditions of the tests.

- Providing the primary design tool for scaling up of the receiver. Simulations of various scaled up receiver models are performed at different radiation input conditions. The receiver geometry and the flow at the entrance and exit are then adjusted to obtain the most effective conditions of energy transport from the concentrated light entering the receiver to the working fluid, while the quartz window is kept at the permitted temperature.

The computational code includes: (i) Models for hydrodynamics, heat convection and radiation transfer in the absorber; (ii) Coupling of the inner receiver continuum models to a statistical(Monte-Carlo) treatment of the external radiation field; (iii) Incorporation of the models within the CFD code PHOENICS

Examples of the computation results are shown in Fig.18a and 18b. Fig. 18a is a three dimensional simulation of a 10 kW experiment. The energy transport is strongly affected by natural convection, much more than was expected when this prototype was designed. Based on the simulation results the asymmetric effect of natural convection was taken into account in the design of the next generation 50 kW receiver. Fig. 18b demonstrates the results of the simulation for the scaled up receiver model.

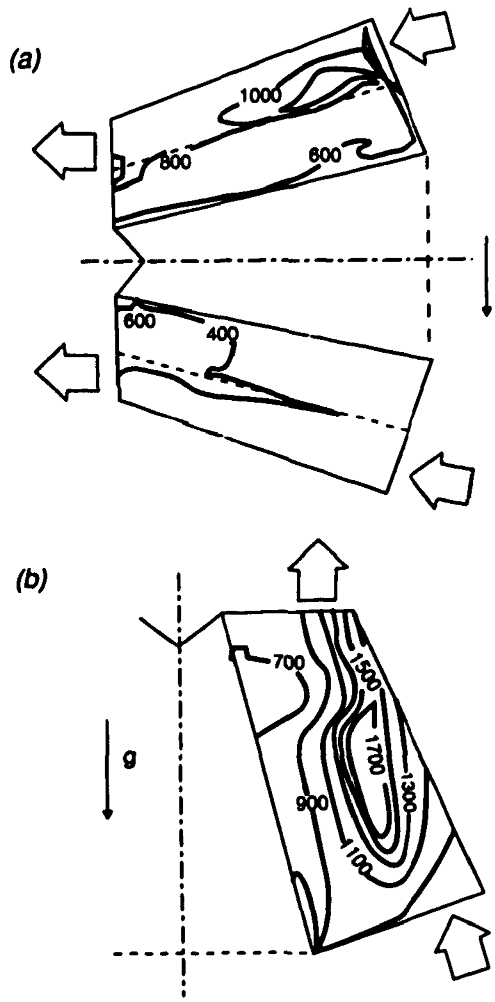


Fig. 18: Flow Simulations -
(a): A 10 kW Horizontal Experiment
(b): A 1MW Vertical Experiment

VII. Experimental Results

The receiver solar experimentation is being conducted at the Weizmann Institute Solar Facilities. Tests were conducted at power levels of 10 and 50 kW. The 10kW tests were performed at the "Solar Furnace", where the receiver was oriented horizontally, i.e., perpendicular to the gravitational field, and the working fluid was CO_2. The 50kW tests are performed at the "Solar Tower", where the receiver is oriented downwards at 25^o to the horizon, and the working fluid is air. 60 type B thermocouples (TC's) are installed in the Porcupine absorber: 48 TC's are distributed around the absorber, positioned at different points along the absorber pins; and 12 TC's are located in the support structure, about 1mm below its hot side surface. 12 type K TC's are used to monitor the temperature of the inlet gas and various receiver components. 2 other type B TC's measure the exit gas temperature. The pressure and flow rates of the working fluid are also measured.

Figure 19 presents a typical temperature distribution in the absorber during a solar tower test. The top, middle and bottom of the legend refer to TC locations on the pin. L is the distance from the receiver aperture to its back end; x/L is the non-dimensional longitudinal location. The relatively low temperature readings at x/L of 0.2 and 0.4 were taken near entrance ports of the coolant. The exit ports are located in the hottest area of the absorber, at the upper part of the absorber $0.7 < x/L < 1$. The operating conditions of this test were:

- -Ambient solar flux= 854 W/m^2.
- -Working pressure = 19 atmospheres.
- -Air flow rate = 0.0409 kg/sec.
- -Air exit temperature = 1130^oC.
- -Receiver power output = 53 kW.

Series of tests at several flow and solar exposure conditions are still being performed at the Weizmann Institute Solar Tower.

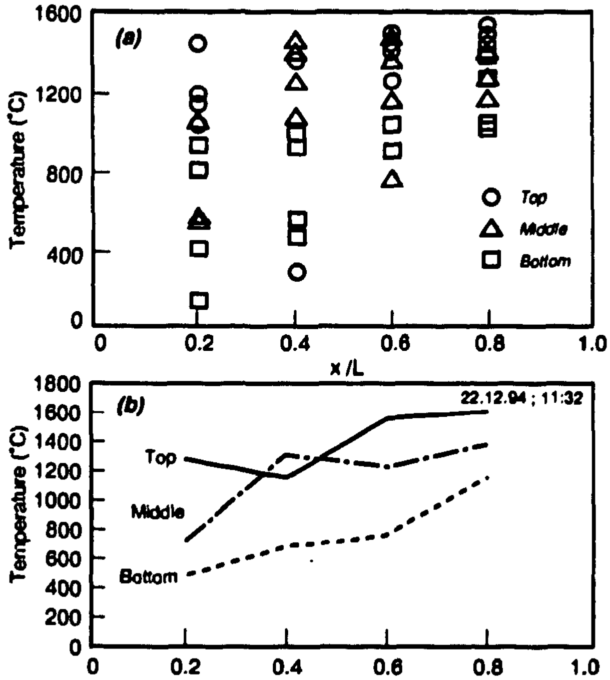


Fig. 19: Examples of Temperature Distribution Over the Absorber in an Actual Test

VIII. Conclusions

The volumetric solar receiver developed in cooperation of NRCN and the Weizmann Institute successfully demonstrated high temperature, high pressure operation, reaching pressures of 10 to 30 atm and air exit temperature exceeding 1000°C. Simulation and analysis indicate that this receiver could be scaled up to commercial capacity to serve as a central receiver in a multi-megawatt solar plant based on direct feeding of an advanced gas turbine. The same receiver , at a power level of about 100kW could also be used with a parabolic concentrating dish to supply power to a Brayton cycle. It could also be used for reforming of hydrocarbons.

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