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The DIAPR: A High-Pressure, High-Temperature Solar Receiver

A solar central receiver absorbs concentrated sunlight and transfers its energy to a working medium (gas, liquid or solid particles), either in a thermal or a thermochemical process. Various attractive high-performance applications require the solar receiver to supply the working fluid at high temperature (900–1500°C) and high pressure (10–35 bar). As the inner receiver temperature may be well over 1000°C, sunlight concentration at its aperture must be high (4–8 MW/m²), to minimize aperture size and reradiation losses. The Directly Irradiated Annular Pressurized Receiver (DIAPR) is a volumetric (directly irradiated), windowed cavity receiver that operates at aperture flux of up to 10 MW/m². It is capable of supplying hot gas at a pressure of 10–30 bar and exit temperature of up to 1300°C. The three main innovative components of this receiver are:

- *a Porcupine absorber, made of a high-temperature ceramic (e.g., alumina);*
- *a Frustum-Like High-Pressure (FLHIP) window, made of fused silica;*
- *a two-stage secondary concentrator followed by the KohinOr light extractor.*

This paper presents the design principles of the DIAPR, its structure and main components, and examples of experimental and computational results.

1 Introduction

Solar thermal technology is currently competitive with fossil fuels only in some very limited markets. The most common example has been water heating in sunny climates; another is the LUZ parabolic trough plants for electric power production in Southern California. Nevertheless, major cost reductions in solar thermal electric power plants are required to achieve significant market penetration. System efficiency improvement and lower capital cost of the plants' principal components are the main areas where substantial cost reduction must be realized.

The Solar Tower is a promising upcoming technology. Here a Central Solar Receiver is stationed at the focus of an array of heliostats, which reflect concentrated solar radiation into it. The sunlight is concentrated in three dimensions and large quantities of solar power (100 MW_t or more) can be harnessed by a single unit. Using secondary concentrators, concentration ratios of 2–10 thousands can be attained and therefore, working temperatures in excess of 1000°C can be reached efficiently in the receiver. Several experimental solar towers were built in the last three decades; the experience gained with them indicates that a key component to the plant's performance is the receiver, i.e., the unit which absorbs concentrated sunlight and transmits its energy to a working fluid in a thermal or thermochemical process.

Various receivers have been proposed and some were developed over the last three decades. 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 solar radiation. The tubes may be arranged on a flat panel at the focal plane of the heliostats (Sandia, 1979), inside a cavity (Epstein, 1990, Grossman et al., 1990), or the solar energy may be transmitted to the tubes by an intermediate high-heat-transfer fluid (Kubo and Diver, 1992).

Directly Irradiated (Volumetric) Receivers. The working fluid either absorbs the radiation directly (Chavez et al., 1990), or is in contact with a solid surface which absorbs the radiation. The absorbing surface may be a stationary matrix (Grasse, 1991; Buck et al., 1991; Karni and Rubin, 1991), or moving particles (Flamant, 1982; Kelbert and Royere, 1990). In some directly irradiated receivers (Grasse, 1991; Flamant, 1982; Kelbert and Royere, 1990) the absorbing matrix is exposed to the ambient. Others (Buck et al., 1991; Karni and Rubin, 1991) have a window, which enables operation under elevated pressure (or vacuum), and utilization of other working gases besides air. The main advantage of these receivers is the ability to absorb relatively high solar fluxes and operate at high temperatures, while using a compact design. Clearly, without a window the use of volumetric receivers is very limited. The development of a dependable window, capable of withstanding high pressure and temperature, has been highly desirable and yet unsuccessful (DeLaquil et al., 1992). As proven by tests, this problem is solved in the DIAPR design presented here.

A receiver capable of operating at the temperature and pressure of modern gas turbines could be integrated with the most efficient power cycles available. The proven thermal to electrical conversion efficiency of cycles such as the Combined Cycle (CC) of gas and steam turbines (Fig. 1), Humid Air Turbine (HAT) and Steam Injected Gas Turbine (STIG), is over 50 percent. As shown in Fig. 1, such a plant could operate in a hybrid mode, using the solar receiver and the combustion chamber either in parallel, or in series. When the radiation input is sufficient, the system can be driven solely by solar power; natural gas would supplement the solar input whenever necessary. The carbon dioxide emission of this plant would be about one-half that of presently operating combined cycle plants, and NO_x and SO_2 emission would also be well below present standards.

Integration with these power cycles requires the receiver to operate at a pressure of 10–30 atmospheres and a temperature of 1000–1500°C (present gas turbine inlet temperature is up to

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1350°C and will reach 1500°C in a few years). To convert solar radiation to heat at this temperature, while minimizing reradiation losses, the concentration of sunlight at the receiver aperture must be 5,000 to 10,000, i.e., 4–8 MW/m^2. Such high concentration levels can be achieved and utilized at high efficiency, using a heliostat field with secondary concentrators and a partitioned central receiver system (Ries et al., 1995; Kribus et al., 1995). Until now, solar thermal receivers were unable to sustain these working conditions. Consequently, the receiver limitations forced many researchers and system designers to suggest applications at relatively low concentration and efficiency. Therefore, the system as a whole could not become competitive.

The Directly Irradiated Annular Pressurized Receiver (DIAPR) is a volumetric (directly irradiated) cavity receiver which operates at a pressure of 10–30 bar, exit gas temperature of up to 1300°C, and aperture radiation flux of up to 10 MW/m^2. Two DIAPR prototypes have been tested at the Solar Furnace and at the Solar Tower of the Weizmann Institute of Science, at nominal power levels of 10 kW$_t$ and 50 kW$_t$, respectively. The DIAPR model can be scaled up for use in a central receiver, combined cycle power generating system (e.g., Fig. 1). It could also be adapted for use with a parabolic dish concentrator and a small gas turbine in a Brayton cycle, where the operating conditions are less demanding than in a CC. Whereas in other solar power generation systems the receiver limitations may restrict the engine operation and limit its efficiency, a DIAPR-type receiver can accommodate any required working conditions for present power conversion devices.

Solar driven chemical processes, such as methane reforming with CO_2 or H_2O, may provide means for long-term storage and long distance transportation of solar energy. Preliminary tests indicate that a DIAPR-type receiver could be an excellent foundation for an efficient high-yield solar methane reforming system.

2 Receiver Design and Main Components

A schematic view of the receiver prototype in two versions is presented in Fig. 2. The three main components of the receiver are as follows.

A Porcupine Volumetric Absorber. A detailed description of the Porcupine absorber and test results are given in Karni and Rubin (1991). The purpose of this component is to absorb concentrated sunlight and transfer its energy to the working fluid. Figures 3(*a*) and 3(*b*) show, respectively, a single absorber block and several blocks assembled together. When all the blocks are assembled, the absorber has a pyramid frustum shape, with its heat transfer elements facing the axis. The absorber elements (i.e., the Porcupine quills) are made of 2 × 3 × 30 mm Alsint alumina or Pythagoras alumina-silica tubes (W. Haldenwanger GmbH & Co. KG). The elements are inserted into a SALI alumina board (Zircar, Inc.), and are secured in place with an alumina cement. The general cooling flow direction is across the elements. The Porcupine absorber has the following advantages: (i) the radiation can penetrate into it such that the absorption process is spread over a large heat transfer area; (ii) it provides an effective mechanism of convective heat transfer to the working fluid; and (iii) its flexible structure prevents the development of thermal stresses, even under steep gradients and transient temperature fields.

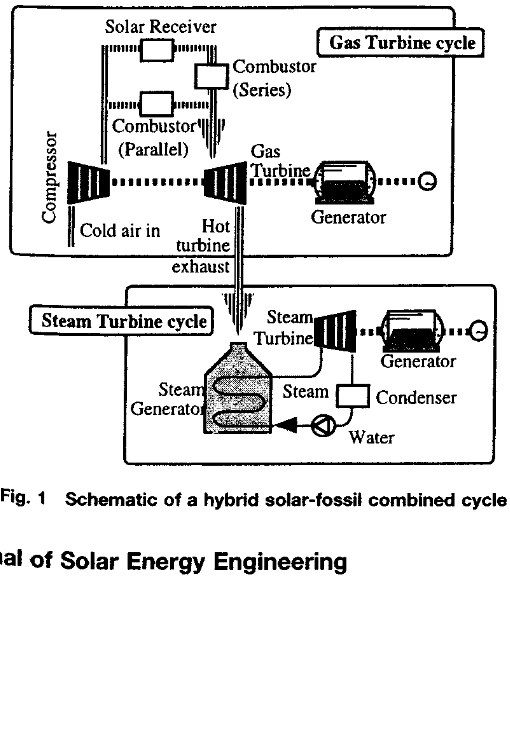

Fig. 1 Schematic of a hybrid solar-fossil combined cycle

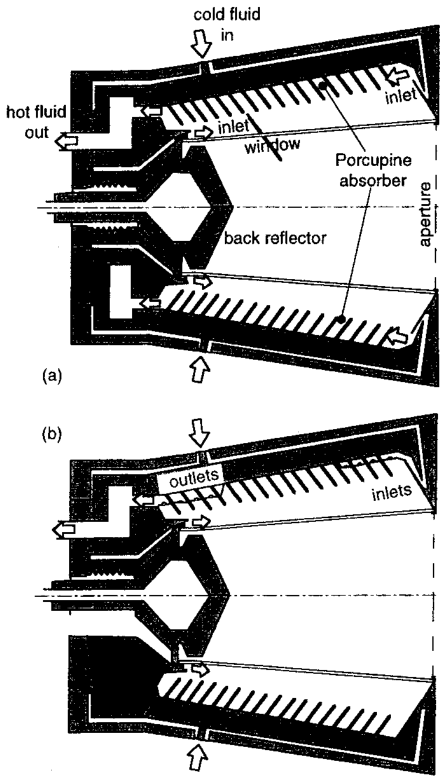

Fig. 2(*a*) "Symmetric" receiver design for the first test series at nominal power level of 10 kW; (*b*) "Asymmetric" receiver design for the second test series at nominal power level of 50 kW

Porcupine absorbers of various construction (different quill length, spacing, flow pattern, etc.) have been tested under a variety of radiation intensities at the Weizmann Institute's Solar Furnace and Solar Tower over hundreds of heating and cooling cycles without any failure.

A Frustum-Like High-Pressure (FLHIP) Window. The design of the fused silica (fused quartz) window is shown in Fig. 4. The purpose of the window is to separate the receiver cavity from the ambient air and allow operation at high pressure, while minimizing reflection losses of solar radiation entering the receiver. It is cooled by the working fluid before the latter reaches the absorber. Analysis and tests show that this window is capable of withstanding a pressure of over 50 bar. The window has not failed in more than a hundred hours of solar tests with the DIAPR, at a pressure of 10–30 bar. The tests also proved that the window is not sensitive to local temperature gradients due to the settlement of contaminants, such as dirt from the upstream piping, ceramic insulation, etc., on its surface. In an early closed-loop test with CO_2 as the working fluid, a large amount of graphite was deposited on the window, coating about 80 percent of its area. Yet, the window was not damaged after about four hours of solar operation at a pressure

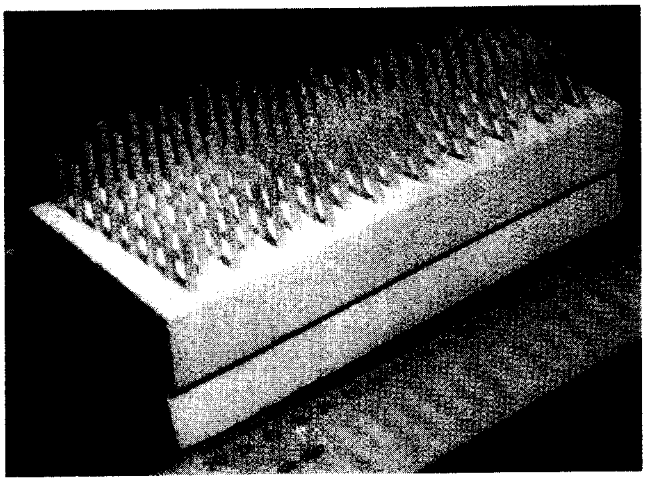

Fig. 3(*a*)

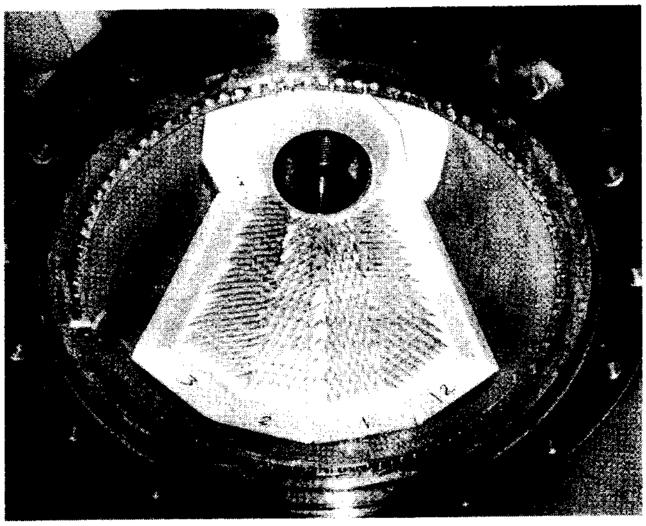

Fig. 3(*b*)

Fig. 3 The Porcupine absorber: (*a*) a single block; (*b*) several blocks installed in the DIAPR cavity

of 20 bar. A similar window can be designed to sustain a pressure of 200 bar. This is achieved by assuring that tensile stresses do not develop at any possible working conditions and thus the window is subject only to compression stresses. 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. Ray tracing calculations indicate that the reflection losses of the window are only about 1 percent, since several reflections are necessary for incoming rays to escape (Kribus, 1994). As seen in Fig. 4, the window thickness is only 2.25 mm and since the fused silica is highly transparent to solar radiation, energy loss due to sunlight absorption is negligible.

A secondary Concentrator and the KohinOr Light Extractor. In the experimental system, the radiation is collected and concentrated initially by the heliostat field onto the secondary concentrator aperture. The secondary concentrator includes three optical stages: (i) a reflective Compound Parabolic Concentrator (CPC); (ii) a dielectric Total Internal Reflection (TIR) concentrator, made of fused silica; and (iii) the KohinOr light extractor, which extracts concentrated sunlight from the high index-of-refraction medium of the TIR concentrator ($n \approx 1.45$) into the receiver cavity ($n \approx 1$), while minimizing back reflection losses. A detailed description of the light extractor is presented in Ries et al. (1996). The three components are shown in Fig. 5.

3 Simulation

Analysis and simulation of the energy transport in the DIAPR are described in Kribus et al. (1994). As demonstrated in Figs. 2(*a*) and 2(*b*), the basic DIAPR design provides for relatively easy modification of the flow pattern in the receiver cavity by adjusting the location of the working fluid inlet and exit and the flow conditions (velocity, flow rate, etc.) at the inlet and outlet. The main objectives of the simulations are

- analyzing experimental data and indicating means to improve heat transfer 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 modifications and scaling up of the receiver. Simulations of various receiver models are performed at different radiation input conditions. The receiver geometry and 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 window is kept relatively cold.

The computational code includes: (i) models for hydrodynamics, heat convection and radiation transfer in the Porcupine absorber; (ii) coupling of the inner receiver continuum models to a statistical (Monte-Carlo) treatment of the external radiation field; and (iii) incorporation of the models within the CFD (Computational Fluid Dynamics) code PHOENICS.

Examples of the computation results are shown in Fig. 6. Figure 6(*a*) is a three-dimensional simulation of a 10 kW experiment. The energy transport is influenced strongly by natural convection; this effect was not given sufficient attention when the first 10 kW prototype was designed (Fig. 2(*a*)), before the simulation code was constructed. Based on the simulation results, the asymmetric effect of natural convection was taken into account in the design of the 50 kW receiver (Fig. 2(*b*)). Figure 6(*b*) presents the results of simulation of a scaled-up receiver model, whose center-line is vertical, and therefore there are no asymmetric effects due to natural convection. The latter example corresponds to a high-concentration large-scale solar plant design (Kribus et al., 1995).

4 Experimental Results

About 250 hours of tests were conducted at nominal power levels of 10 and 50 kW. The 10 kW tests were performed at

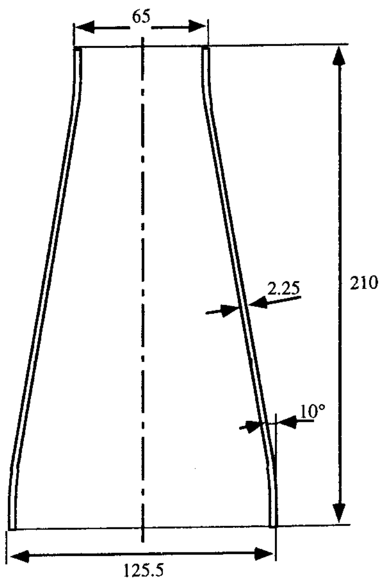

Fig. 4 Design of the frustum-like high-pressure (FLHIP) window. Dimensions are in millimeters.

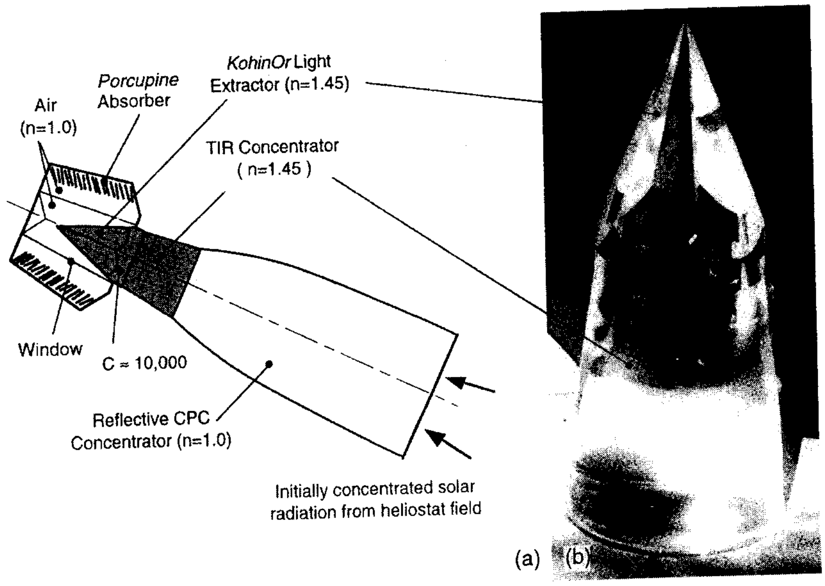

Fig. 5(*a*) Schematic presentation of the secondary concentrator, light extractor, and receiver; (*b*) the KohinOr light extractor

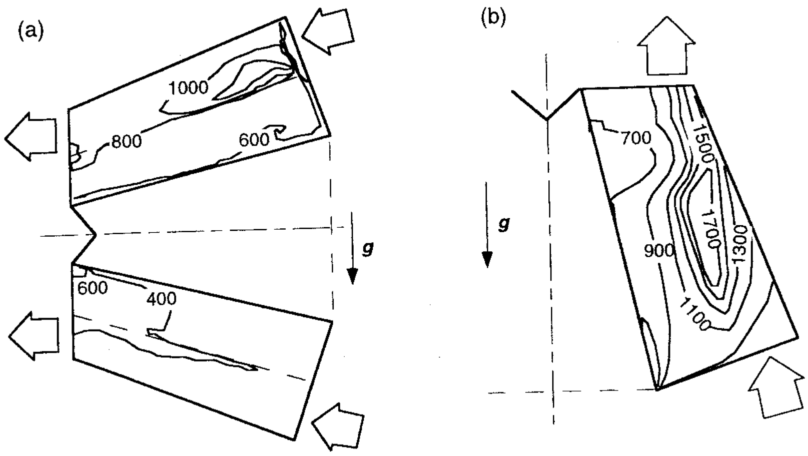

Fig. 6 Isotherms in °C from simulations: (*a*) simulation of the 10 kW experiment, installed horizontally with asymmetric natural convection effect; (*b*) an upscaled vertical 1MW DIAPR

the Solar Furnace of the Weizmann Institute, where the receiver was oriented horizontally, i.e., perpendicular to the gravitational field, and the working fluid was CO_2. The 50 kW tests were performed at the Solar Tower, where the receiver is oriented downwards at 25 deg to the horizon, and the working fluid is air. The receiver was subjected to more than a hundred abrupt heating-cooling cycles with no adverse effects.

64 Type B thermocouples (TC's) are installed in the Porcupine absorber. They are distributed around the absorber in groups of four. In each group, one TC is installed about 1 mm from the top of a Porcupine quill (i.e., farthest from the base support and closest to the receiver center-line), another near the middle of an adjacent quill, a third about 1 mm from the bottom of a neighboring quill and a fourth is positioned nearby inside the support structure, about 1 mm below its hot-side surface. 12 Type K TC's are used to monitor the temperature of the inlet gas and various receiver components. Two type B and one type K TC's measure the exit gas temperature. The working pressure, pressure difference from the receiver inlet to outlet, and flow rate of the working fluid are also measured. The window temperature is measured by an infrared (10 μm)

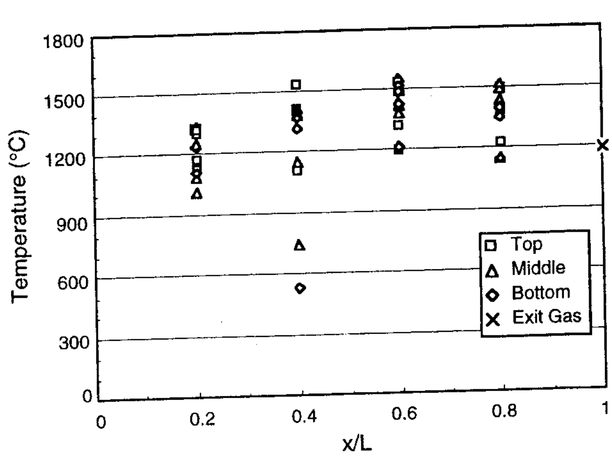

Fig. 7 Temperature distribution in the DIAPR during a test. See text and Table 1 for details.

Table 1 Operating conditions and test results for June 23, 1996, 13:59 p.m. corresponding to Fig. 7

Insolation	870 W/m^2
Working pressure	18.0 bar
Air mass flow rate	0.0222 kg/s
Air inlet temperature	35°C
Air exit temperature	1204°C
Receiver power output	30 kW
Pressure difference across receiver	0.25 bar
Window maximum temperature	600°C

camera looking in, with the aid of a mirror, through the CPC aperture. For the purpose of the IR measurements, the dielectric parts of the secondary concentrator were replaced by a ring-shaped aluminum adapter, and the receiver operated at a somewhat lower inlet concentration and power level.

Figure 7 presents a typical temperature distribution in the absorber during a test. The operating conditions of this test are given in Table 1. The "Top," "Middle" and "Bottom" of the legend refer to TC locations in the absorber element. L is the axial length of the receiver, and x/L is the nondimensional axial distance from the aperture plane. TC's from several circumferential locations are shown together in the figure. The average absorber temperature increases as x/L increases from 0 to 0.6 and remains at the same, relatively high level at $x/L \geq 0.6$; therefore the exit ports, which are located in the back part of the absorber, at $0.7 < x/L < 1.0$, are in the hottest area of the absorber. As Fig. 7 demonstrates, the effect of natural convection on the temperature field was negligible, relative to radiation and forced convection. This is expected in a high-temperature, high-energy flux receiver.

The input of solar power into the receiver was calculated using ray tracing to be 38 kW. The receiver efficiency in this experiment is therefore about 79 percent; typically the receiver efficiency was about 80 percent. Simple modifications, such as adding insulation to the outer body, and optimization of the receiver operation would significantly increase its efficiency.

In all the measurements the error is up to ± 3 percent, except for the window temperature, where the error is about ± 10 percent. The ray tracing calculations assume some empirical values and may have an error of ± 10 percent.

5 Conclusions

The Directly Irradiated Annular Pressurized Receiver (DIAPR) is a volumetric (directly irradiated) cavity receiver which was shown experimentally to operate at a pressure of 10–30 bar, exit gas temperature of up to 1300°C and aperture radiation flux of up to 10 MW/m^2. Simulation and analysis indicate that this receiver could be scaled up and therefore operate in a multimegawatt central receiver plant and supply power to a high-temperature gas turbine. A DIAPR-type receiver, at a power level of about 100 kW could be used with a parabolic concentrating dish to supply power to a Brayton cycle. It could also be used for reforming of hydrocarbons.

The Weizmann Institute and Rotem Industries are presently working to further improve the DIAPR, scale it up, and demonstrate its integration with a gas turbine plant. More experimental and analytical data will be published in the near future.

Acknowledgments

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