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OPTIMIZED SECONDARY CONCENTRATORS FOR A PARTITIONED CENTRAL RECEIVER SYSTEM

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Abstract—We present secondary concentrators with non-regular shapes for increasing the concentration of radiation from a given field of heliostats, well suited for partitioning the receiver into several units, arranged side by side. For a general heliostat field with a non-axisymmetric directional distribution of the radiation at the entrance aperture of the secondary concentrator, concentrators with non-regular shape can significantly increase the concentration as compared to their symmetric analogs. Our optimizations indicate best results for concentrators based on rectangular entrance and exit apertures. The concentration may be increased by a factor of 2.3 at an optical efficiency of 90%. If the shape of the exit aperture is required to be close to circular, concentrators based on non-regular hexagonal apertures may reach concentration higher than their symmetric analogs by a factor of 1.3. For the given radiation, concentrators with polygonal apertures perform significantly better than concentrators with smooth elliptic apertures.

1. INTRODUCTION

Standard nonimaging concentrating reflectors, such as the Compound Parabolic Concentrator (CPC) (Rabl, 1976a; Welford and Winston, 1989), may perform close to the thermodynamic limit for radiation incident on the aperture from an axisymmetric cone of directions (Ries, 1982; Welford and Winston, 1989). If, however, the radiation available at the entrance aperture is non-axisymmetric, the performance of a CPC secondary may decrease seriously, reducing efficiency and/or concentration.

The radiation produced by a heliostat field onto a central receiver can have a rather complicated distribution in the four-dimensional phase space of radiation (two position coordinates and two directional coordinates), which is not easy to visualize, nor to describe in simple analytic terms. But one can use two projections onto mutually perpendicular two-dimensional subspaces to help visualization. The *flux distribution* is the relative intensity as a function of position in the focal plane, independent of the arrival direction of the rays. The flux distribution is commonly referred to in the context of absorbers deployed in the focus. In contrast the *directional distribution* is the relative intensity as a function of arrival direction independent of position. The directional distribution is essential when secondary concentrators are to be used. This (quasi-) separation is possible, because of the small angle of the sun. In particular in the center region of the target, the angular extent of the radiation is independent of location. Therefore the integration over the two dimensions of position is similar to a cross section. In the case of a solar tower the directional distribution is determined by the contour of the field, as seen from the focus. For an axisymmetric directional distribution a heliostat field with the center displaced from the tower would need to be delimited by an ellipse with the long axis pointing away from the tower. This is visualized in Fig. 1a. Such an arrangement would involve a large spread in distances between heliostats and is therefore not desirable. In fact most noncircular heliostat fields tend to have the shorter axis pointing away from the tower as shown in Fig. 1b. This arrangement leads to a strongly asymmetric directional distribution.

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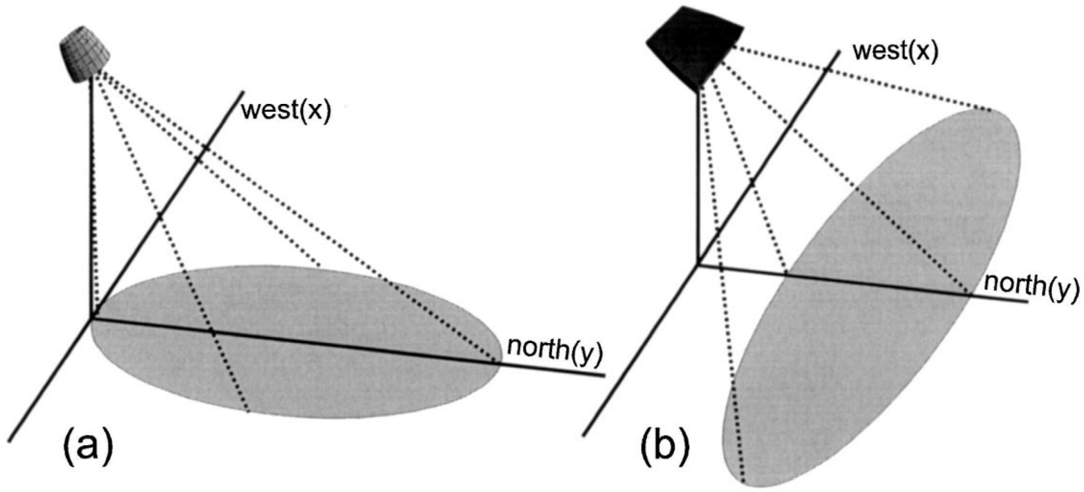

Fig. 1. Elliptical contour of a north-field accepted by an axisymmetric secondary concentrator (a). Schematic view at an east–west wide field, such as at the Weizmann Institute (b).

2. GENERAL APPROACH

2.1. Partitioning

Recent developments for high performance solar tower plants suggest partitioning the receivers into several sections to which the heat transport fluid is fed consecutively. The sections are thus acting in parallel with respect to the radiation and at the same time in series with respect to thermal transport. One reason for partitioning the receiver is better thermal performance (Ries *et al*., 1995; Doron and Kribus, 1996; Kribus *et al*., 1999). Another incentive for receiver partitioning results from power limitations for a single receiver. Naturally, simultaneously partitioning the receiver and the secondary concentrator calls for polygonal entrance apertures adequate to tile the focal zone, i.e. cover it with several apertures arranged side by side without gaps. Systems consisting of several secondary concentrators with regular polygonal entrance apertures arranged side by side have recently been constructed and demonstrated (Buck *et al*., 1998; Kribus *et al*., 1999; Yogev *et al*., 1999). If the entrance aperture is polygonal it seems particularly practical to design the entire concentrator from plane facets.

This was the motivation for investigating in this paper the potential of various concentrator concepts of regular and non-regular shape. We define concentrators to be of ‘regular shape’ if their apertures have the form of circles or regular polygons. The concentrators called ‘non-regular’ have apertures in the form of ellipses or non-regular polygons. The concentrators with circular or elliptic apertures have smooth surfaces. The concentrators with polygonal apertures in the shape of hexagons or rectangles were designed of plane or one-dimensionally curved facets which can be constructed from thin planar glass mirrors. The concentrators with a smooth surface are not suited to tile the focal region of a heliostat field, but are presented as a reference case.

In this paper we analyze the performance of a single concentrator representing the whole array of a partitioned receiver system. The concentrator is positioned at the center of the focal spot. Because the concentrator is part of an array, its entrance aperture is small compared to the focal spot of the heliostat field. We choose the entrance aperture to intercept about 10% of the field’s radiation.

2.2. The radiation

The entrance apertures we considered are positioned in the center of the focal region of the heliostat field corresponding to the location of the high-temperature stage of a partitioned receiver system. We modeled the input radiation based on a dense continuum field idealization (Riaz, 1976; Spirkl *et al*., 1998) within an elliptical contour that approximately matches that of the experimental field at the Weizmann Institute (see Fig. 1b). Each small heliostat directs a cone of radiation with a Gaussian directional distribution with 11 mrad full width at half maximum towards the center of the focal zone at the tower. Fig. 2 shows the flux distribution as equally spaced iso-flux lines in arbitrary units in the focal plane of this idealized heliostat field as well as the suggested placement of the entrance aperture of a hexagonal

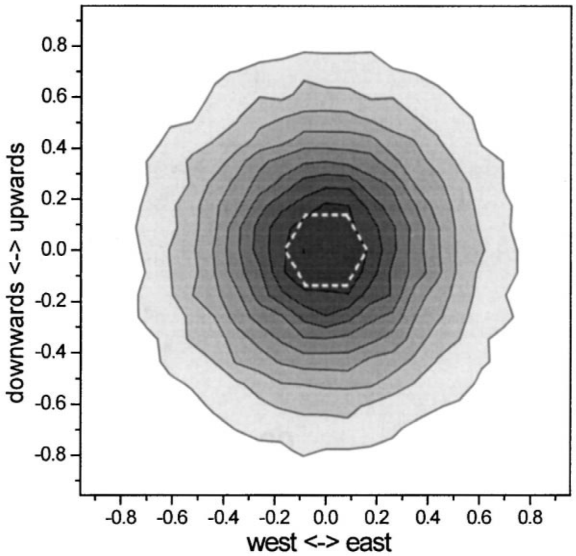

Fig. 2. Distribution of radiation in the focal plane of the heliostat field. A hexagonal entrance aperture is shown as a dashed line. The shape of the entrance aperture can vary while the area is kept constant.

high temperature stage. This aperture is sized such as to intercept roughly 10% of the total power reflected from the heliostats.

The shape of the heliostat field results in a strongly non-axisymmetric directional distribution of the radiation. As seen from the target of the heliostats the radiation falls within a cone with half opening angle of about 12° in the N–S and 40° in the E–W direction. Moreover this cone is not uniformly filled. The directional distribution of our model radiation at the small aperture in the center of the focal plane is shown in Fig. 3. The radiation fills an elliptic envelope in directional space that represents the shape of the heliostat field. The inhomogeneities within the envelope are considerably small. The deviations from the average are below 10%. This is characteristic for the center of the target where the radiation is composed of the central part of the spots produced by all single heliostats.

The radiation intercepted by the small aperture in the center of the focal plane of the field is the input radiation for the optimized concentrators presented in this contribution. Since we allow for irregular entrance apertures the shape of the aperture might vary. The resulting changes in intercepted radiative power and directional distribution are very low (smaller than 1% relative change of intercepted power) due to the homogeneity in the flux distribution on the center of the

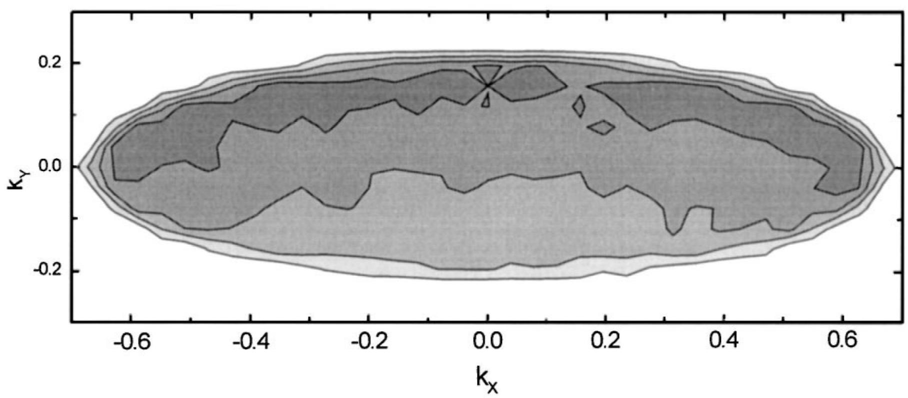

Fig. 3. Directional distribution of the radiation at the center of the target. The radiation fills an elliptic region in directional space. The directional space is defined by the components of the projection of a ray's unit vector onto the secondaries entrance aperture plane. *kx* is the projected directional component in east–west direction, *ky* is the projected directional component in north–south direction.

focal plane. The transmission efficiency of every concentrator is referred to the radiative power intercepted by the concentrator's entrance aperture.

Standard nonimaging concentrators are intended for radiation coming out of an axisymmetric circular cone which appears as a circle in a directional distribution plot such as Fig. 3. The purpose of our research was to find new concentrator geometries adapted to the elliptic envelope of the field's radiation in directional space. The inhomogeneities of the radiation within the envelope do not affect the geometry of concentrators designed for high efficiency. The new concentrator geometries should concentrate homogenous radiation from an elliptic cone with two different opening angles.

Since the target plane is positioned in the focal plane of the heliostat field the radiation at the periphery is also coming from the whole field. Thus the directional distribution of the intercepted radiation fills the same envelope but with strong inhomogeneity. This is due to the fact that more distant heliostats contribute more radiation to the periphery than the nearer heliostats. When using the concentrators presented in this contribution at the periphery, the inhomogeneity bares an additional potential for improvement. This potential could only be used with shapes of even less symmetry, e.g. concentrators without symmetry in a north–south cross-section.

2.3. Optimization by means of ray-tracing

Analytic design methods for designing a concentrator for the non-axisymmetric radiation as described above are not available. Methods such as the edge-ray tailoring (Friedman *et al*., 1993) have not yet been extended to three dimensions.

We start with an arbitrary approach by assembling a basic concentrator shape from two different cross-sections in east–west and south–north direction. We vary this basic shape, while the areas of the inlet and exit apertures are kept constant. The transmission efficiency of the resulting concentrator, i.e. the fraction of the radiative power intercepted by the entrance aperture that is transmitted to the exit aperture; is evaluated by ray-tracing for the particular radiation distribution described above and realistic optical properties, e.g. 95% reflectivity. The optimal shape is then found numerically by maximizing the transmission (Shatz and Bortz, 1995; Spirkl *et al*., 1997, 1998). The number of rays used in the ray-trace is sufficient to reduce the statistical error to less than 1%.

2.4. Characteristic curves for concentrators

For the concentration of radiation there are in general two conflicting objectives: high average flux at the exit aperture and high optical efficiency. We will refer to the flux concentration, i.e. the ratio of the average flux density at the exit and the entrance aperture, simply as concentration. High concentration at the exit aperture of the concentrator leads to higher possible process temperatures and less thermal radiation losses. High transmission leads to higher overall efficiency (Pitman and Vant-Hull, 1986; Duffie and Beckman, 1991). The losses in concentration or optical efficiency can be either absorption losses due to imperfect reflectivity of the reflecting surfaces or rejection losses, i.e. radiation that is not transmitted to the exit aperture but turned back within the concentrator. Rejected radiation emerges from the concentrator through the entrance aperture.

To assess the performance of a concentrator concept, one needs the entire characteristic curve, which plots the achievable concentration as a function of the optical efficiency. A full characteristic extends from a point with unit optical efficiency and no concentration to a point with the maximum concentration allowed by thermodynamics and zero transmission. Each point represents the highest concentration at that particular optical efficiency and at the same time the highest optical efficiency at that particular concentration (Spirkl *et al*., 1997, 1998).

We obtain the characteristic curve by optimizing concentrators of the same geometric approach but with different exit aperture sizes. Large exit apertures lead to high transmission but low concentration. Small exit apertures lead to high concentration but low transmission efficiency.

In the final layout of a plant, the desired temperature of the thermal process determines the working point on the characteristic curve and hence the choice of the concentrator exit aperture area (Pitman and Vant-Hull, 1986).

3. GEOMETRIC APPROACHES

We investigated concentrators with circular, elliptic or polygonal apertures. We will refer to an aperture as *regular* in case it has the shape of a circle or a regular polygon. We will refer to an aperture as *non-regular* in case it has the shape of an ellipse or a non-regular polygon. All apertures show the east–west symmetry and the north–south symmetry of the radiation considered for the design of the concentrators.

To investigate the possible improvement with non-regular designs we investigated three different concepts.

(a) The *regular/regular* concept has a regular entrance and a regular exit aperture.

(b) The *non-regular/regular* concept has a non-regular entrance aperture and a regular exit aperture.

(c) The *non-regular/non-regular* concept has a non-regular entrance aperture and a non-regular exit aperture.

Type (b) concentrators were dictated by the practical need to interface with the circular entrance aperture of a high-pressure receiver (Karni *et al*., 1997; Buck *et al*., 1998). It allows for non-regular shapes but the exit aperture is restricted to fit the circular high-pressure windows with minimal gaps.

3.1. Smooth surface

Although we envision practical concentrators to be built from facets, we also included smooth concentrators for comparison. The classes of smooth concentrators we included in our investigation have a parabolic shape in the axial cross section in both planes of symmetry: in the east–west and north–south plane. The two branches of one cross-section belong to the different parabola but are symmetric to the central axis of the concentrator, similar to the CPC. In contrast to the CPC, however, the position of the focal point of the parabola for each cross-section and the axial extension of the concentrator are both subject to the optimization. The entire surface is defined by interconnecting these two cross-sections with ellipses. The eccentricity of the entrance and the exit aperture are also optimized. This gives, together with the axial extent of the concentrator, seven free parameters for the optimization. Table 1 gives the number of free parameters of all considered concentrator shapes.

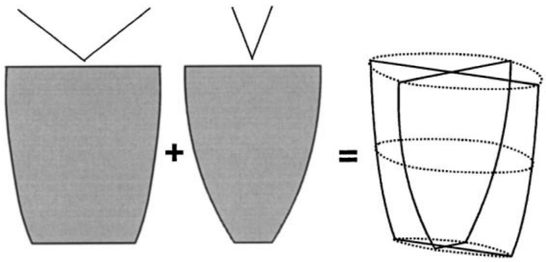

Fig. 4. The asymmetric concentrator with the smooth surface is designed out of two different profiles in the north–south cross-section and the east–west cross-section, intended to accept radiation out of different opening angles. The different profiles are interconnected by ellipses.

Fig. 4 illustrates the geometric design. Fig. 5 shows two concentrators of this class.

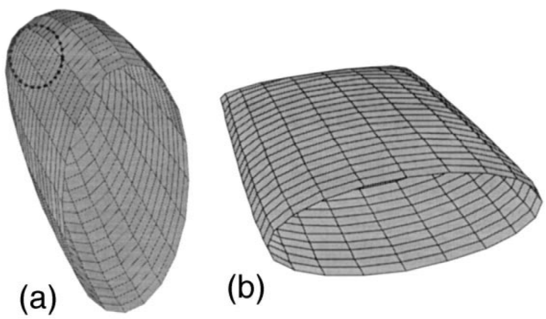

Fig. 5. Two different optimized concentrators with smooth surface. Both have a non-regular entrance aperture. (a) Non-regular/regular concept with circular exit aperture, (b) non-regular/non-regular concept with elliptic exit aperture.

Table 1. Number of free parameters for optimization for the considered concentrators

Number of free parameters for optimization	Regular/regular concept (a)	Non-regular/regular concept (b)	Non-regular/non-regular concept (c)
Concentrators with smooth surfaces	3	6	7
Concentrators with hexagonal apertures and two axial segments	3	7	9
Concentrators with rectangular apertures and two axial segments	3	5	6
Concentrators with rectangular apertures and three axial segments	5	8	9
Concentrators with rectangular apertures and one-dimensionally curved facets	3	6	7

3.2. Hexagonal apertures with plane facets

Concentrators with hexagonal entrance apertures have the advantage that the focal zone can be tiled with them. We distinguish two types of non-regular hexagons: one with two horizontal sides (H-type) and one with two vertical sides (V-type). A concentrator composed of plane facets can have entrance and exit apertures corresponding to any of the four combinations shown in Fig. 6. Two parallel sides can be interconnected with a trapezoidal facet. Nonparallel sides need two triangles. One axial segment connecting two hexagonal apertures can contain 12 triangular or two trapezoidal and eight triangular facets, as shown in Fig. 6, depending on the type of apertures it is interconnecting. Fig. 6 shows the possibilities of interconnecting two hexagonal apertures of the same type or different types by plane facets. We optimized concentrators composed of two and three such rings of facets or axial segments as visualized in Fig. 7.

3.3. Rectangular apertures with plane facets or one-dimensional curved facets

We also optimized concentrators with rectangular apertures. Two rectangular apertures can simply be interconnected by four trapezoidal facets building one axial segment. As a limiting case of an infinite number of axial segments, we also considered concentrators built out of four facets curved in one dimension. Because the Gaussian curvature is zero, such facets can be constructed by bending thin sheets. We allowed general parabolic shapes, without any restriction of similarity to a CPC. Fig. 8 shows examples of concentrators with rectangular apertures.

Note that two non-regular hexagonal apertures cannot be interconnected by facets with one-dimensional curvature because opposite sides are not parallel. The facets would be twisted and hence would have two-dimensional curvature.

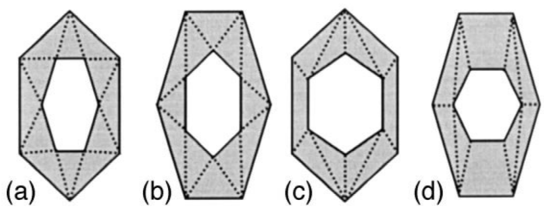

Fig. 6. Various types of interconnections between non-regular hexagonal apertures by plane facets. (a) V-type to H-type, (b) H-type to V-type, (c) V-Type to V-type, (d) H-type to H-type. The interconnections between the non-parallel sides by triangular facets in (c) and (d) are not unique.

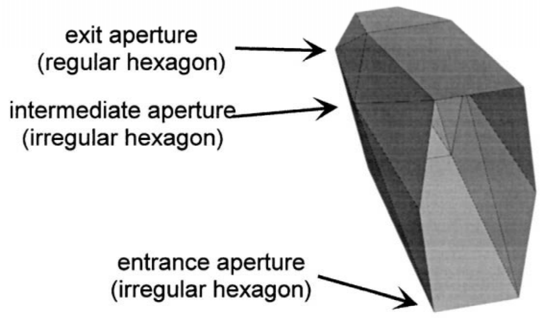

Fig. 7. Concentrator with hexagonal apertures and plane facets. It is built out of two axial segments interconnecting apertures of the H-type. Hence, it is composed of four trapezoidal and 16 triangular facets. The entrance aperture and the intermediate aperture are irregular hexagons. The exit aperture is a regular hexagon. In that specific case there are eight geometric parameters free for optimization. See Table 1 for the number of free parameters of all considered concentrator shapes.

4. RESULTS

The results of the optimizations are shown as characteristic curves for each type of concentrator investigated. Each single point on a characteristic curve is a different concentrator individually optimized for a given exit aperture area. We assumed 95% reflectivity for all incidence angles for the reflecting surfaces throughout the calculations. Back surface silver coated glass mirrors which can provide this reflectivity are available.

4.1. Concentrators with smooth surface

Fig. 9 shows the characteristic curves for concentrators with smooth surfaces and the three concepts. The non-regular/regular concept (b) and the non-regular/non-regular concept (c) perform significantly better than the regular/regular concept (a) for the given radiation. They reach higher concentration for a given transmission efficiency and higher transmission efficiency for given flux concentration.

At 90% transmission the non-regular/regular concept (b) and the non-regular/non-regular concept (c) reach a concentration higher than that of the regular/regular type concentrator (a) by a factor of 1.42 and 1.45, respectively. Comparing concepts (b) and (c), it is clear that the non-regular/non-regular concept (c) does not perform significantly better than the non-regular/regular concept (b). This shows that non-regular shape is more important at the entrance than at the exit for smooth concentrators. At transmission values above 90% the optimized type (c) concentrators resemble the shape shown in Fig. 5b. Below 90%

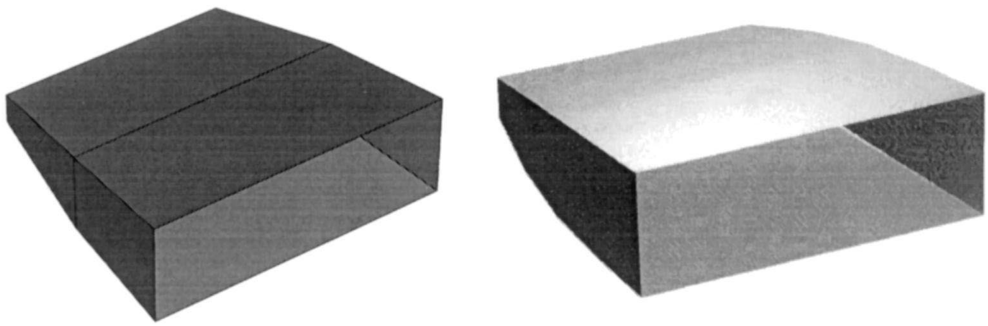

Fig. 8. Concentrators with rectangular apertures. The left one is built out of eight trapezoidal facets arranged in two axial segments. The right one is built out of four one-dimensional curved facets with parabolic curvature.

optical efficiency the optimized non-regular/non-regular concentrators are identical with the non-regular/regular concentrators as illustrated in Fig. 5a. This is an unexpected result. Although type (c) concentrators have one additional degree of freedom, this degree degenerates leading to the same shape and result as optimized type (b) concentrators in the regime of relatively high concentration.

4.2. Concentrators built of plane facets

We investigated all the various ways to connect hexagonal apertures by plane facets described above and found that the concentrators connecting only apertures of the H-type as shown in Fig. 6d performed best. Consequently we present only the results of this type of concentrator with hexagonal apertures together with the results for the concentrators with rectangular apertures.

Fig. 10 shows the characteristic curves for concentrators designed of plane facets. Concentrators with hexagonal apertures (diamonds) are compared to concentrators with rectangular apertures (squares). All concentrators are composed of two axial sections.

For the regular/regular concept (a) the hexagonal concentrators perform slightly better than the rectangular concentrators. The non-regular/regular concept (b) performs significantly better as compared to the regular/regular concept (a). Within the non-regular/regular concept (b) the concentrators with rectangular apertures perform slightly better than the concentrators with hexagonal apertures.

The relative concentration of the non-regular/regular concept (b) compared to the regular/regular concept (a) at 90% transmission is higher by a factor of 1.30 for hexagonal apertures and 1.37 for rectangular apertures. The concentrators with rectangular apertures perform slightly better over the entire range. For the non-regular/non-regular concept (c) the characteristic curves for concen-

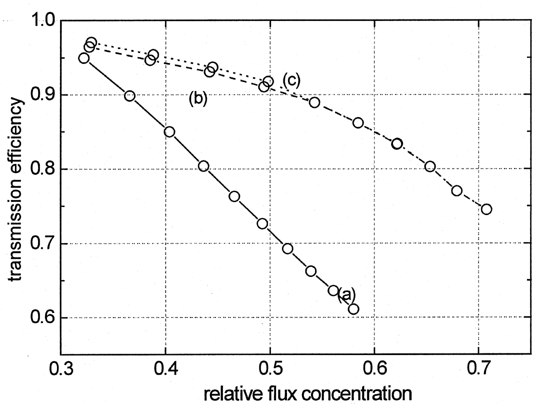

Fig. 9. Characteristic curves for optimized concentrators with smooth surfaces. (a) Rotationally symmetric regular concentrators, (b) non-regular/regular concentrators, (c) non-regular/non-regular concentrators. The flux concentration is normalized to the thermodynamic limit.

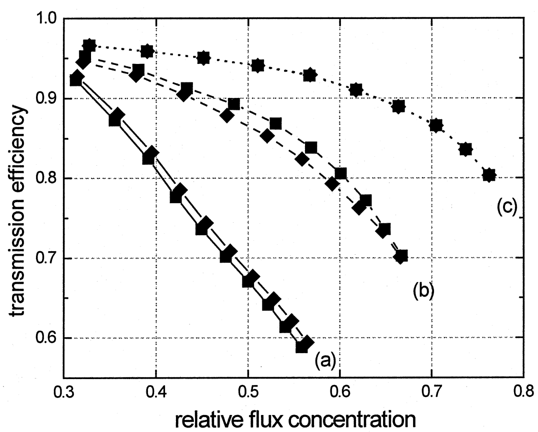

Fig. 10. Characteristic curves for optimized concentrators built of plane facets with hexagonal apertures (diamonds) or rectangular apertures (squares): (a) regular/regular concentrators, (b) non-regular/regular concentrators, (c) non-regular/non-regular concentrators. For non-regular/non-regular concentrators, optimal hexagonal apertures degenerated into rectangles.

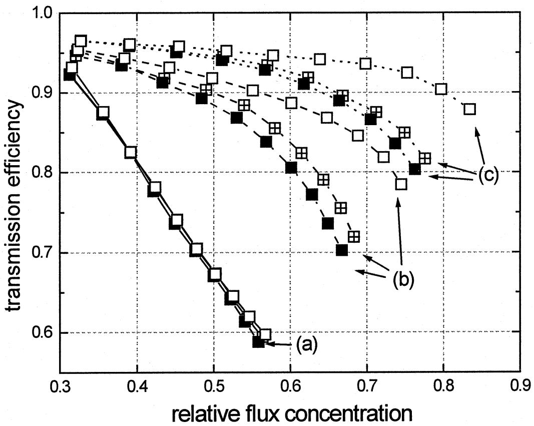

Fig. 11. Characteristic curves for concentrators with rectangular apertures and different axial subdivisions. The solid squares correspond to concentrators with two axial subdivisions as in Fig. 10. The cross-centered squares correspond to concentrators with three axial subdivisions. The open squares correspond to concentrators built of one-dimensional curved facets. The curves are shown for the three concepts (a), (b), (c).

trators with rectangular and hexagonal apertures are identical within the statistical error. This is an unexpected finding because concentrators with hexagonal apertures have more degrees of freedom than rectangular aperture concentrators. Indeed, for concept (c), the concentrators with rectangular apertures are a subset of the concentrators with hexagonal apertures. In the results from the optimization we also found that the hexagonal apertures degenerated into rectangles. We found a concentration of the non-regular/non-regular concept (c) higher by a factor of 1.8 than the regular/regular concept (a) at 90% transmission.

4.3. Influence of the number of axial subdivisions

Fig. 11 shows the characteristic curves for concentrators with rectangular apertures and different numbers of axial subdivisions. The curves are shown for two and three subdivisions and one-dimensionally curved facets as a limiting case of an infinite number of axial subdivisions.

For the regular/regular concept (a) additional axial subdivisions offer only marginal improvement. On the other hand, additional axial subdivisions lead to significant improvement in performance, both for the non-regular/regular concept and the non-regular/non-regular concept. The flux concentration with asymmetric concentrators built out of four one-dimensionally curved facets (Fig. 8b) is higher by a factor of 2.3 at 90% transmission compared to the regular/regular concept. The one-dimensional curved facets were limited to have a parabolic profile. The two profiles for the facets in both cross-sections were optimized. We found that the optimal concentrator does not resemble a 2-D CPC. The concentrators resulting from optimization therefore differ from crossed CPCs investigated by Rabl (1976b), Molledo and Luque (1984), and Brunotte *et al.* (1996).

4.4. Comparison of the geometric approaches

Fig. 12 compares the characteristic curves for the concentrators with smooth surfaces and the concentrators with rectangular apertures. Within the regular concentrators of type (a) concentrators with smooth surfaces perform better than those built of facets. However, for the non-regular/non-regular concept (type c) all faceted concentrators

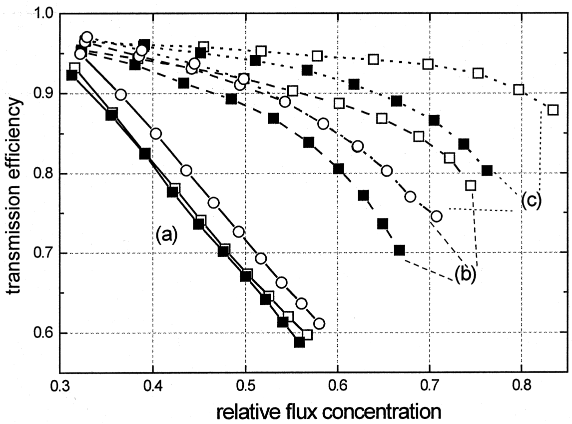

Fig. 12. Characteristic curves of the concentrators with smooth surfaces (open circles), concentrators with rectangular apertures built of plane facets with two axial sections (full squares) and concentrators with rectangular apertures built of one-dimensional curved facets (open squares).

perform significantly better than those with smooth surfaces. This is an unexpected result, since we usually regard faceted concentrators as approximations of a smooth shape, and therefore expect them to have lower performance. For the non-regular/regular concept (b), the concentrators with smooth surfaces perform better than the relatively simply constructed concentrators with two axial segments but worse than the concentrators built of one-dimensional curved facets.

The non-regular/non-regular concentrator of concept (c) with rectangular apertures and one-dimensional curved facets reaches 80% of the thermodynamic maximum of concentration at 90% collection efficiency. The concentrator with a smooth surface reaches only 52% under the same condition. Therefore we conclude that subdivisions (smoothing) in the axial direction present an advantage whereas subdivisions in the circumference do not. This is corroborated by the finding that rectangular apertures outperform hexagonal ones.

We do not have an analytical explanation for the finding that the concentrators with rectangular apertures perform so well. A qualitative argument could be that the rectangular cross-section to some extent allows for a separation of the concentration in east–west and north–south direction. Since the opening angles of the radiation in these cross-sections are significantly different, the rectangular concentrators could benefit from this quasi-separation.

It could be shown that faceted concentrators optimized for homogeneous radiation out of an axisymmetric directional range benefit from finer subdivisions leading to a smoother shape (Timinger *et al*., 2000). This is obviously not true for the radiation with non-axisymmetric directional distribution considered in this contribution. The concentrators with the best performance have rectangular apertures rather than smooth apertures.

5. CONCLUSIONS

We have investigated the radiation concentration at the central region of the target in an elliptic heliostat field. The most characteristic feature of the available radiation is the highly eccentric directional distribution. In line with expectations, concepts for a secondary concentrator which allow for non-regular apertures lead to significant improvement in transmission or concentration for the available radiation. The concentration with non-regular concentrators at 90% collection efficiency is higher by a factor of 2.35 than for regular concentrators.

The performance of the concentrators benefits from additional subdivisions in the axial cross-section all the way to one-dimensionally curved facets as a limiting case. Contrary to expectations, we found that the performance does not benefit from many subdivisions of the aperture. For the given radiation the best concept we found is a non-regular concentrator with rectangular entrance and rectangular exit aperture connected by four one-dimensionally curved leaves.

In further contributions we will present optical and thermal (Kribus *et al*., 2000) measurements on the concentrator in Fig. 8a, that was built and tested at the WIS. We will also document the performance of optimized concentrators with rectangular apertures and one-dimensional curved facets for homogenous radiation out of an elliptical cone of directions with various angular extents and eccentricities.

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REFERENCES

Brunotte M., Goetzberger A. and Blieske U. (1996) Two-stage concentrator permitting concentration factors up to 300× with one-axis tracking. *Solar Energy* **56**, 285.

Buck R., Abele M., Kunberger J., Denk T., Heller P. and Lüpfert R. (1998) Receiver for solar-hybrid gas turbine and combined cycle systems. In *Proceedings of Solar Thermal Concentrating Technologies, Odeillo, France,* Flamant G., Ferriere A. and Pharabod F. (Eds.), p. 537.

Doron P. and Kribus A. (1996) Receiver partitioning: a performance boost for high-temperature solar applications. In *Proceedings of the 8th Symposium on Solar Thermal Concentrating Technologies, Cologne, Germany*, Becker M. and Böhmer M. (Eds.), p. 621.

Duffie J. A. and Beckman W. A. (1991). *Solar Engineering of Thermal Processes*, John Wiley, New York.

Friedman R. P., Gordon J. M. and Ries H. (1993) New high-flux two-stage optical designs for parabolic solar concentrators. *Solar Energy* **51**, 317.

Karni J., Kribus A., Ostraich B. and Kochavi E. (1997) A high-pressure window for volumetric solar receivers. *J. Solar Energy Eng*. **120**, 101.

Kribus A., Doron P., Karni J., Rubin R., Taragan E. and Duchan S. (1999) Multi-stage solar receivers: the route to high temperature. In *Proceedings of ISES Solar World Congress, Jerusalem*.

Kribus A., Huleihil M., Timinger A. and Ben-Mair R. (2000) Performance of a rectangular secondary concentrator with an asymmetric heliostat field. *Solar Energy*, In press.

Molledo A. G. and Luque A. (1984) Analysis of static and quasi-static cross compound parabolic concentrators. *Appl. Optics* **23**, 2007.

Pitman C. L. and Vant-Hull L. (1986) Performance of optimized solar central receiver systems as a function of receiver thermal loss per unit area. *Solar Energy* **6**, 457.

Rabl A. (1976a) Comparison of solar concentrators. *Solar Energy* **18**, 93.

Rabl A. (1976b) Optical and thermal properties of compound parabolic concentrators. *Solar Energy* **18**, 497.

Riaz M. R. (1976) A theory of concentrators of solar energy on a central receiver for electric power generation. *J. Eng. Power* **98**, 375.

Ries H. (1982) Thermodynamic limitations of the concentrations of electromagnetic radiation. *J. Opt. Soc. Am.* **A72**, 380.

Ries H., Kribus A. and Karni J. (1995) Non-isothermal receivers. *J. Solar Energy Eng.* **117**, 259.

Shatz N. and Bortz J. (1995) An inverse engineering perspective on nonimaging optical design. In *Proceedings of SPIE: Nonimaging Optics: Maximum Efficiency Light Transfer III, San Diego*, Winston R. (Ed.), p. 136.

Spirkl W., Ries H., Timinger A. and Muschaweck J. (1997) Optimized compact secondary reflector for parabolic troughs with tubular absorbers. *Solar Energy* **61**, 153.

Spirkl W., Timinger A., Ries H., Muschaweck J. and Kribus A. (1998) Non-axisymmetric reflectors concentrating radiation from an asymmetric heliostat field onto a circular absorber. *Solar Energy* **63**, 23.

Timinger A., Kribus A., Doron P. and Ries H. (2000) Facetted concentrators optimized for homogeneous radiation. *Appl. Optics*, In press.

Welford W. T. and Winston R. (1989). *High Collection Non-Imaging Optics*, Academic Press, New York.

Yogev A., Fisher U., Erez A. and Blackmon J. (1999) High temperature solar energy conversion systems. In *Proceedings of ISES Solar World Congress, Jerusalem*.