EXPECTED OPTICAL PERFORMANCES OF NOVEL TYPE MULTI-ELEMENT HIGH-HEAT SOLAR CONCENTRATORS

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ABSTRACT

Basic concept and principles of forming the focal spot in an innovative one-stage high-heat solar concentrating system are discussed. The concentrating system employs the multi-element approach and consists of a nested set of concave ring elements with the inner reflecting surfaces having variable slope and curvature. The reflecting elements are coaxially disposed in a manner to prevent mutual screening of both incident and concentrated fluxes. Such a ring-array concentrator (RAC) shapes its focal zone on its rear side and sufficiently remote from the lower edges of reflecting elements thus providing the lens-like functioning.

Employing the computer simulation and visualization of optical caustics, the irradiance focal distribution is obtained and analyzed for various reflecting surface profiles of RAC elements. In particular, it is shown that utilizing the parabolic profiles for reflecting surfaces may allow to achieve a record one-stage concentration approaching the thermodynamic-photometrical limit for the most of an incident flux. The so high concentrating ability unattainable by other one-stage concentrators becomes possible in RAC due to the cumulative contribution of individual reflective elements. Each of the RAC ring reflecting elements forms its own focal spot with the peak concentration of about several thousands. Concentric superposing the individual focal spots yields extraordinary flux densities in the common focus. Based on computer simulation results, we also discuss RAC dimensional characteristics and slope/tracking error tolerances.

1. INTRODUCTION

Current development of module approach to solar energy utilization, which can provide numerous mediate and direct high-heat solar techniques, requires an efficient, inexpensive and operation-convenient concentrating optics as a key component. Among the one-stage high-heat concentrators, the dish-parabolic mirror remains the most known and usable, despite it does anything but meet all requirements.

It is generally accepted, that the maximum attainable sunlight concentration with an optically ideal dish-parabolic mirror makes on the average in the focal spot, where 90 % of incident flux being concentrated, without provision for the real darkening to solar disk edge, about $2.4x10^4$ suns for the rim angle of 2ϕ~110° and, accordingly, slightly more than $1.1x10^4$ suns in the spot, where total flux is concentrated with $2\phi = 90°$ (see e.g. Johnston, 1998; Feuermann et al., 1999). The concentrations, practically attainable with parabolic dishes manufactured with technologies at acceptable cost, are so lagging behind these values, that the experts firmly consider them reaching frontier. Thus, the measured peak concentration in a focal spot of 5-m parabolic dish reflector, using the “facet” technology of gluing of 2300 flat mirror tiles on a fiberglass shell, made 970 suns (Johnston, 1998).

Improvement of optical performances with more complex methods of manufacturing the dish-parabolic concentrators, for instance, similar to those used for production of mirrors of large optical telescopes, results in inadequate rise in price of solar modules, where the concentrator’s cost share is usually the largest. And, lastly, the necessity of front disposition of receivers/absorbers in relation to the dish-parabolic mirrors essentially restricts both the convenience in their operation and maintenance, and the range of high-temperature solar technologies employing them. For a long run these circumstances have hampered the progress in reaching the scale of use of high-concentration solar optics devices, which would correspond to their high potential perspective and multi-functionality.

This paper discusses and theoretically studies an innovative type of high-temperature solar concentrators, the so-called ring-array concentrators (RAC). The expected optical performance of RAC exceeding that of dish-parabolic mirrors and simultaneously improving the operation performances and manufacture allowance prompt for considering the design as an ultimate improvement of reflective solar optics.

2. DESCRIPTION OF RAC CONCEPT AND COMPUTER SIMULATION METHOD

The concentrating system employs the multi-element approach and consists of a set of concave ring reflecting elements (Vasylyev, 1982, 1996, 1998). The elements having variable slope and curvature of the inner reflecting surface are disposed coaxially in a manner to prevent the mutual screening of both incident and concentrated fluxes – see Fig. 1.

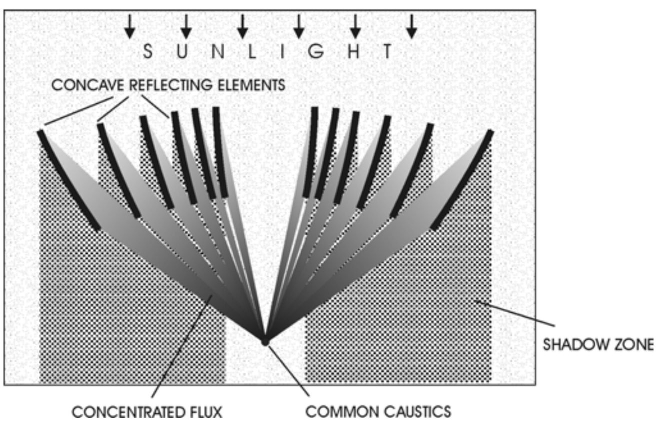

Fig. 1: The sectional view of RAC optical design and its sunlight ray paths.

As Fig. 1 shows, the concentrator, being an essentially reflective system, acts like a lens by forming the focal zone on its rear side and sufficiently remote from the lower edges of reflecting elements. This virtually eliminates any restrictions on possible type and size of the absorber and enhances the operating and maintenance convenience when the RAC devices are applied for various high-temperature techniques.

With the purpose of finding and analyzing the expected RAC optical performance the focal spot parameters for various reflecting surface profiles of RAC elements have been obtained through computer simulation and visualization of optical caustics. In order to support the calculations of this unique optical scheme, RAC-specific mathematical technique and computer software were developed. It allowed to utilize the ray tracing technique to calculate and plot a true scale two-dimensional image of the focal spot as well as the curves for irradiance distribution and concentration ratio along any of its section.

The calculations were performed in the framework of geometric optics only and without provisions for energy losses due to scattering and absorption. However, coma aberration and solar disk edge darkening for the maximum of solar radiation spectrum have been accounted for.

Irradiance distributions have been obtained for different types of RAC which reflective elements were represented by parabolic, circular, and polygonal generatrices. Similar calculations and computer simulation were performed also for an ideal dish-parabolic concentrator to compare the results and verify the method.

3. RESULTS AND DISCUSSION

Fig. 2 shows the theoretical curves of concentration ratio distribution along the focal spot diameter, formed by RAC ($2\phi=140°$) and by dish-parabolic concentrator ($2\phi=110°$), obtained with the above-said method. The concentrated energy has been normalized to the sunlight flux incident on the concentrator active area, as required by the energy conservation law, so that the rotation figure volumes for all curves are identical.

In Fig. 2, curves 1-3 correspond to reflecting elements which generatrices have parabolic, circular and polygonal profiles, accordingly. Curve 4 corresponds to a dish-parabolic concentrator. The focal spot size is normalized for thousandth of concentrator diameter D_c. The dashed curve shows the distribution formally corresponding to standard thermodynamic-photometrical limit. This latter curve was not normalized for the real darkening of solar disk to its edge, which is considered for the remaining curves.

The indicated rim angle values are taken such as they correspond to peak concentration of both optical systems, averaged for 90% of focal spot, which in practice is a more important performance characteristic of the concentrator than the average concentration in a total spot. Comparison of the parameters of total focal spots formed by these concentrators shows that their parameters hardly differ with small (about 5–10%) advantage of RAC in the range of rim half-angles 55°– 80°. However, in the focal spot core, the RAC collecting advantage is much more pronounced.
The analysis of obtained data shows that the average concentration within 90% of RAC focal spot with parabolic profiles of reflecting surfaces exceeds almost three-halfs

that for the dish-parabolic concentrator. These ratios are generally preserved for the focal spots accounting for 70% and 80% of the incident solar flux. When large rim angles of RAC are used, the peak concentrations in the focal spot center almost twice exceed the values usually taken as thermodynamic-photometrical limit and considered record even in practice of using the two-stage solar concentrators. Furthermore, as Fig. 2 shows, even for more manufacturing friendly circular and polyline profiles of reflecting elements, the RAC concentration ability may exceed the optimized dish-parabolic one in limits of focal spot core.

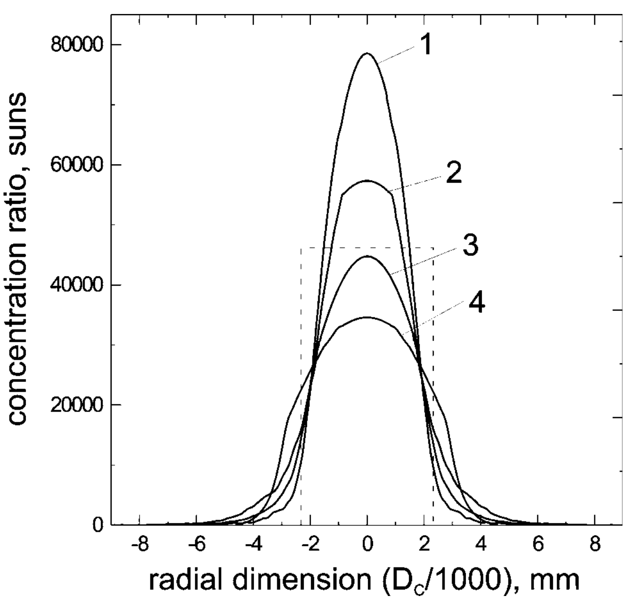

Fig. 2: Comparison of RAC concentrating abilities.

It's important to note that, according to our results, the use of a more realistic model of the solar disk with darkening to its edge increases the peak and average concentration ratios in the central zone of focal spot approximately by 40% and 20%, respectively, keeping constant the values for total focal spots. Using our approach for calculating an ideal dish-parabolic concentrator and utilizing a simple model with homogeneous solar disk distribution of brightness gives the results that are in good agreement with the generally accepted data, that confirms the correctness of the method used.

In order to understand the RAC operation principle it is important to take into account it is essentially non-imaging optical system even though it may have parabolic profiles of reflecting surfaces. Each point on the solar disk is generally imaged as a ring encircling the concentrator axis. Nevertheless, this does not prevent the creation of very high densities of solar radiation in a focal spot and reduces the effect of inherent aberrations on its reflective surfaces.
In point of fact, so high RAC concentrating ability is due to each of its ring reflecting elements creating a relatively small focal spot with peak concentration of about some thousands. The total focal spot is hereby formed by superposition of energy fluxes reflected from individual surfaces of RAC elements.

The study of the rim angle value dependence on average concentration in the focal spot core has shown that the RAC concentrating ability for 2ϕ being 90° to 180° drops no more than by 15–20 % to this range bounds. The RAC compares favorably with the dish-parabolic concentrator, for this latter the range of rim angles, corresponding to such a drop, being almost 2.5 times smaller. Another essentially positive difference is the RAC rim angle optimum range being not in the 2ϕ smaller than 120° region, as in the dish-parabolic case, but on the contrary it lies in the range of large angles. Thus, the "RAC + target/absorber" system can be at least twice more compact, as compared with the parabolic dish.

The developed method also allows to investigate the slope/tracking errors influence on the focal spot parameters. Such study has shown, that the error amount up to angles of about half-radius of the solar disk not only change the peak and average values of concentration in a focal spot core insignificantly, but also, in difference from dish-parabolics, do not shift the spot relatively to the RAC axis, i.e. practically, relatively to the target/absorber centre. The RAC property is important both in view of its manufacturing tolerance, and for keeping the target/absorber exposure constant under operating conditions. One more important advantage, which the RAC optical performances ensure, will be the increase of reflection coefficient with simultaneous impairment of accuracy of the reflecting cover on its elements owing to skew sunlight incidence.

4. CONCLUSIONS

The results allow to conclude that the RAC can be considered as a very efficient solar concentrator system allowing to achieve top concentration in the focal spot while employing the single-stage reflection. Certainly, it can also be coupled with the secondary concentrators of known types for better efficiency. As the RAC optical system has multi-element structure, it can be adopted to a wide range of specific high-temperature technologies by varying the reflecting element number and parameters.

Furthermore, unlike dish-parabolic solar concentrators, the RAC devices can be much more compact providing very easy access to the sub-concentrator target/absorber, that is especially important in system mounting, use, and servicing.

The outstanding optical characteristics of RAC, such as low dependence of focal spot parameters on aperture angle, limited tracking errors and reflecting element bending deflection, as well as reflective material used, prerequisite the successful development of a simple and inexpensive production technique for such concentrators.

The range of potential applications of RAC includes high-efficiency concentrating PV and Stirling-engine solar power generators, as well as thermal concentrating collectors and high-temperature solar furnaces.

5. REFERENCES

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